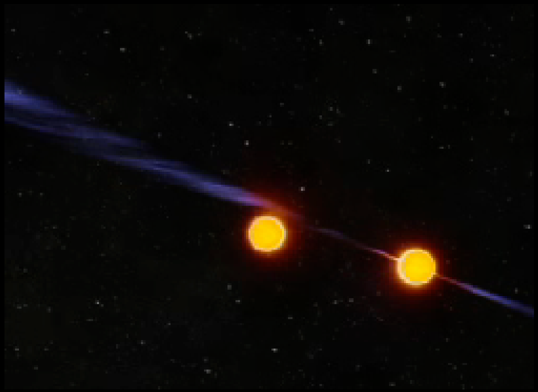


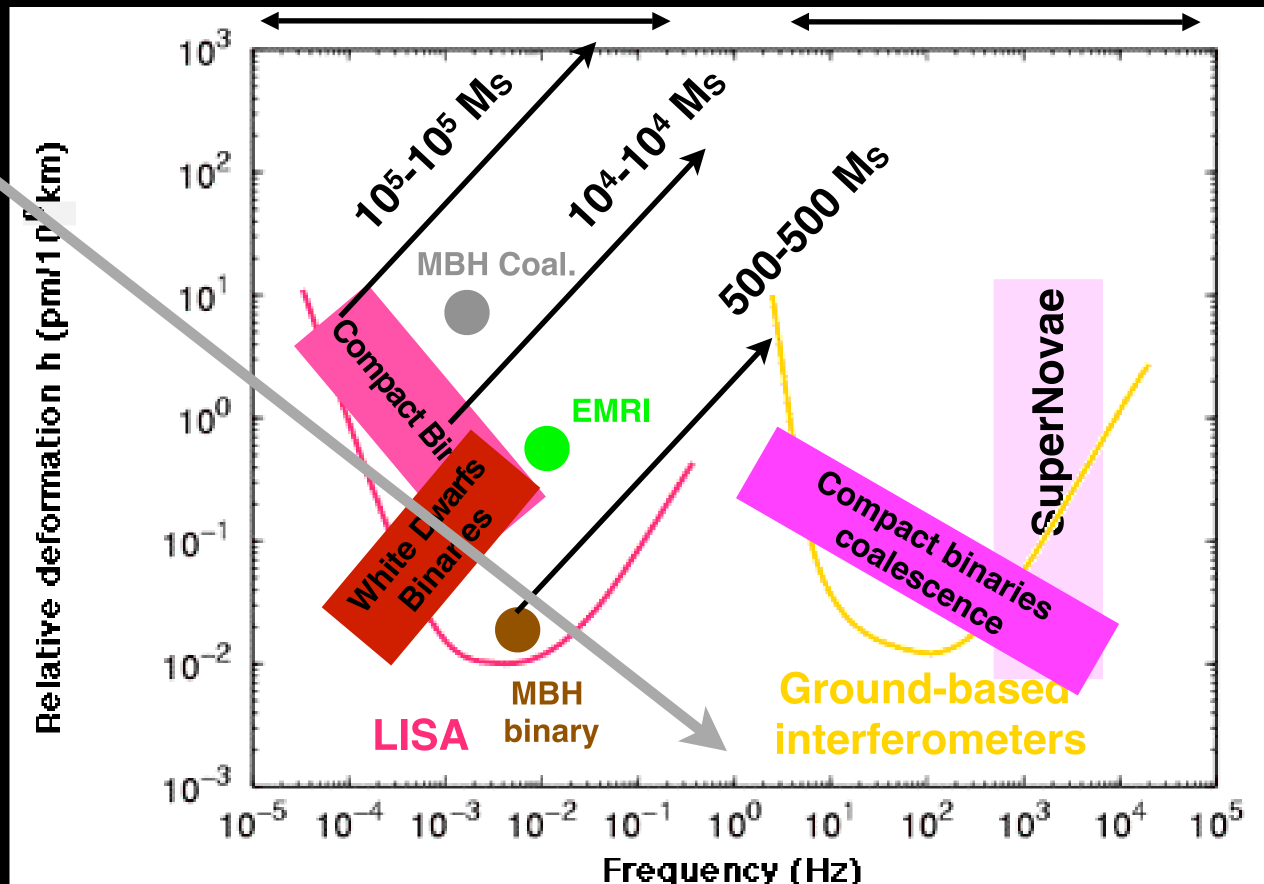
- Preparation of the data analysis of the gravitational wave space antenna.
  - 1) LISA (Laser Interferometer Space Antenna) Why?
  - 2)How?

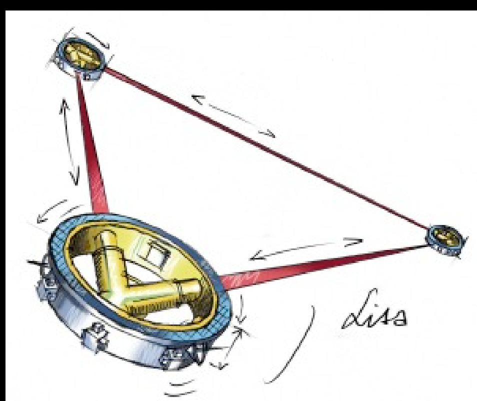
Frequency Limitation

$$f = \frac{c}{\lambda} \approx \frac{c}{L} \rightarrow L \approx 5\,10^6 \text{ kms}$$

Periodic sources *burst sources*

Seismic noise cannot be cancelled at low-frequency





From the earth to the Stars

Science Goal

LISA frequency band : 10^{-4}-10^{-1} Hertz

LISA science goal complementary to ground based interferometer

- Short-period known galactic binaries
- Mergers of massive (10^5-10^8 M_{sun}) and intermediate mass (10^2-10^4 M_{sun})
- Compact objects (NS, BHs) spiralling into massive and intermediate mass BH

- Astrophysical stochastic background : WD-WD galactic and extragalactic
- Gravitational wave signals from the early universe

Massive Black Hole

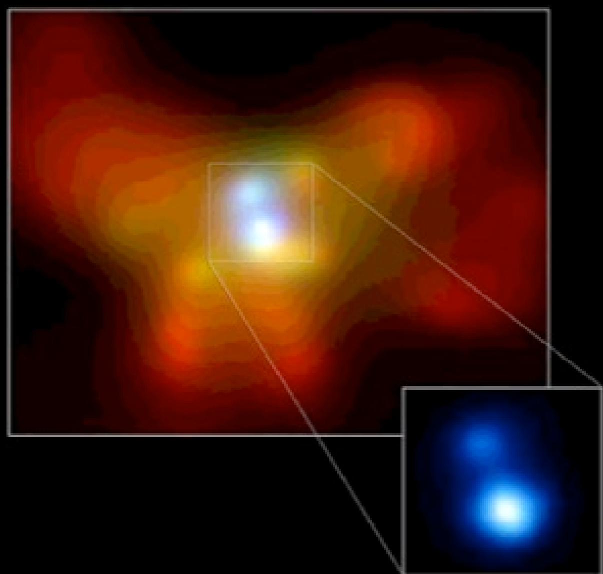
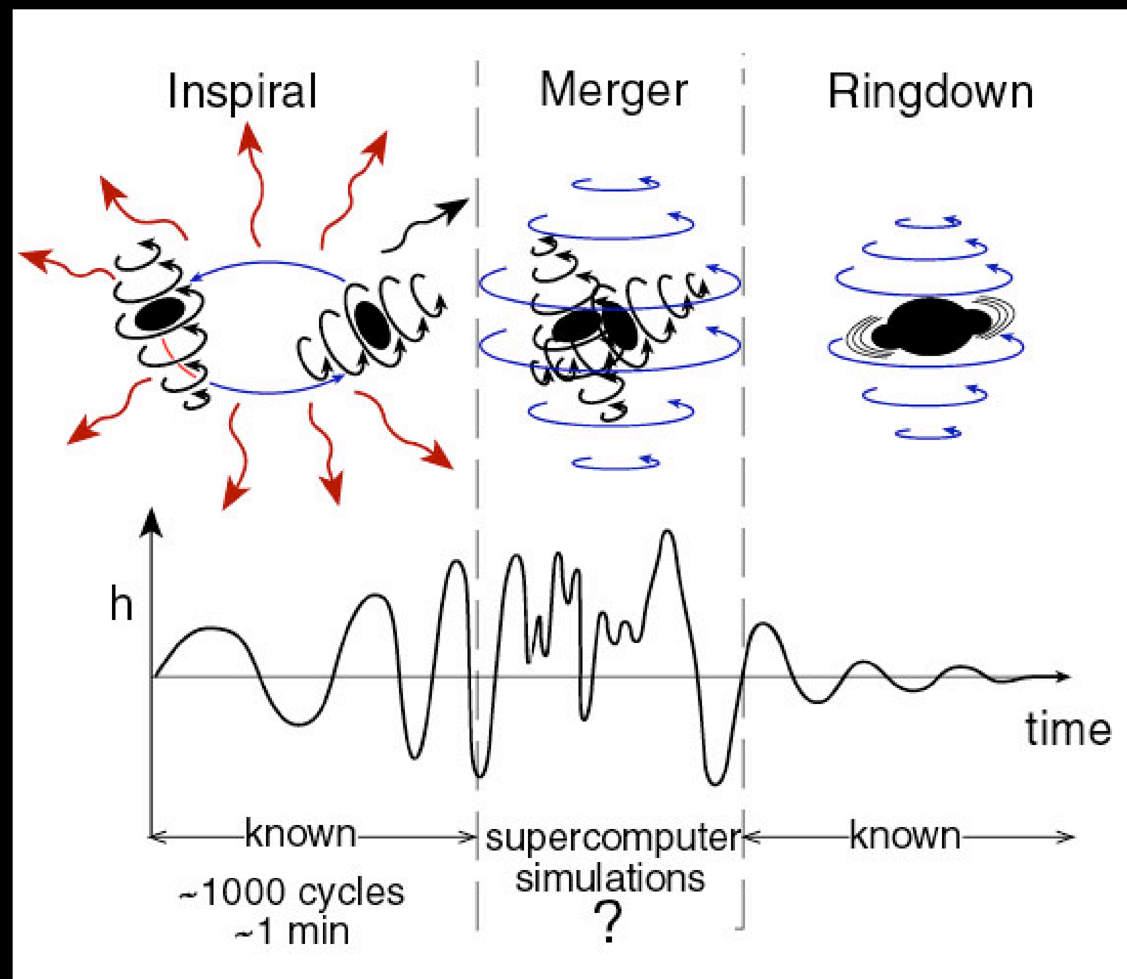


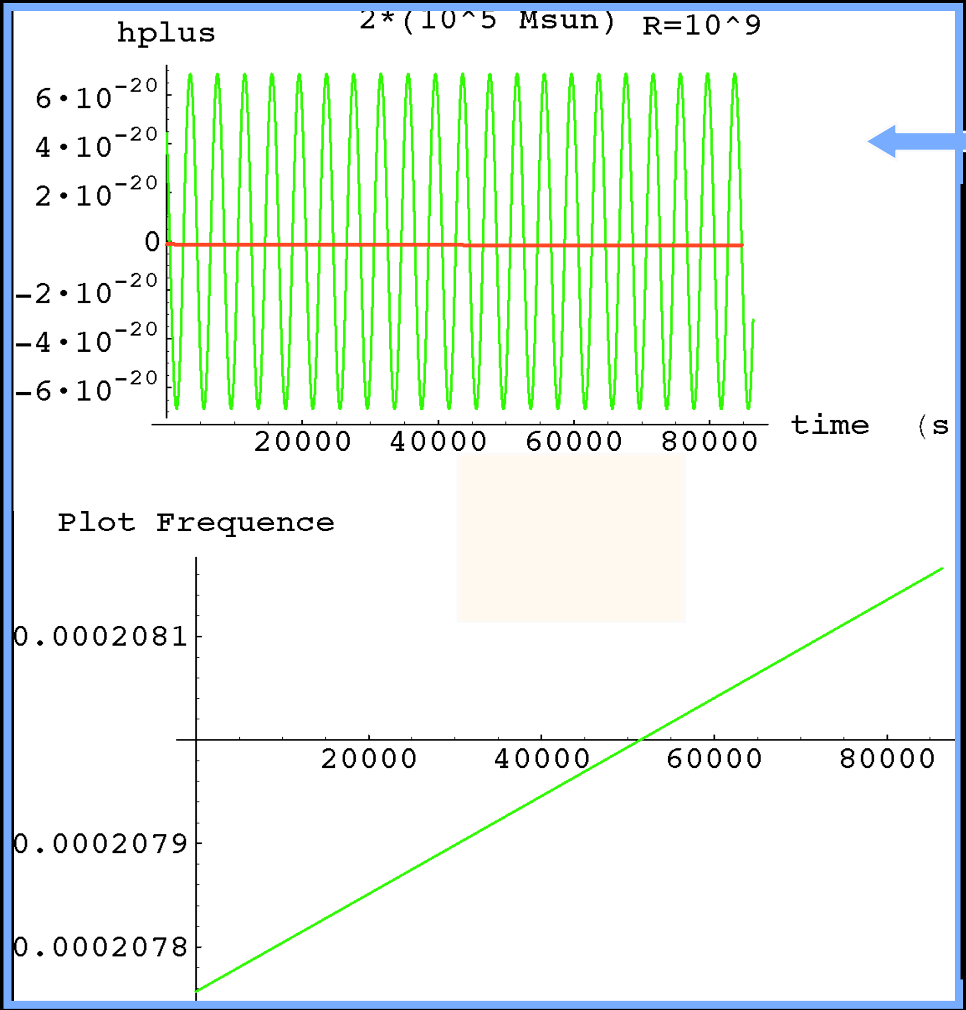
Image of NC6240 taken by Chandra
Showing a butterfly shaped galaxy
Product of two smaller galaxies
(two active giant BH)

Post Newtonian

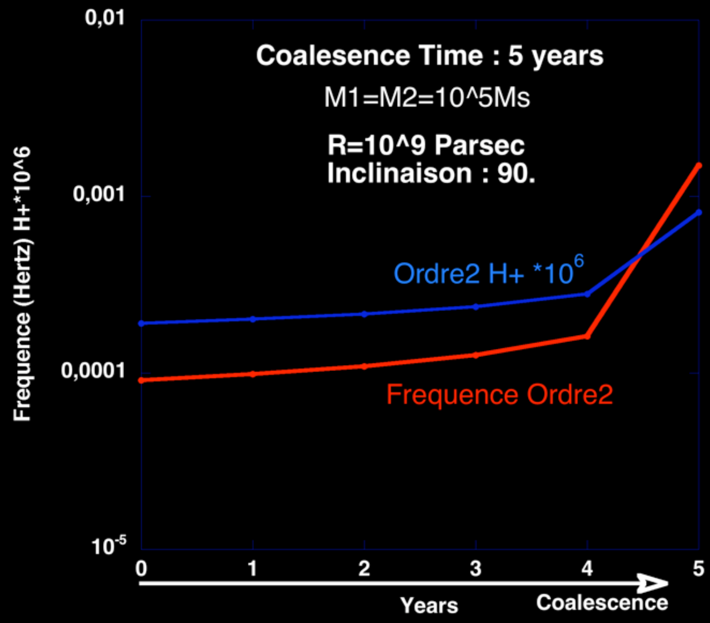
Numerical relativity



Massive Black Hole cont.



Post Newtonian calculation
10 days before coalescence



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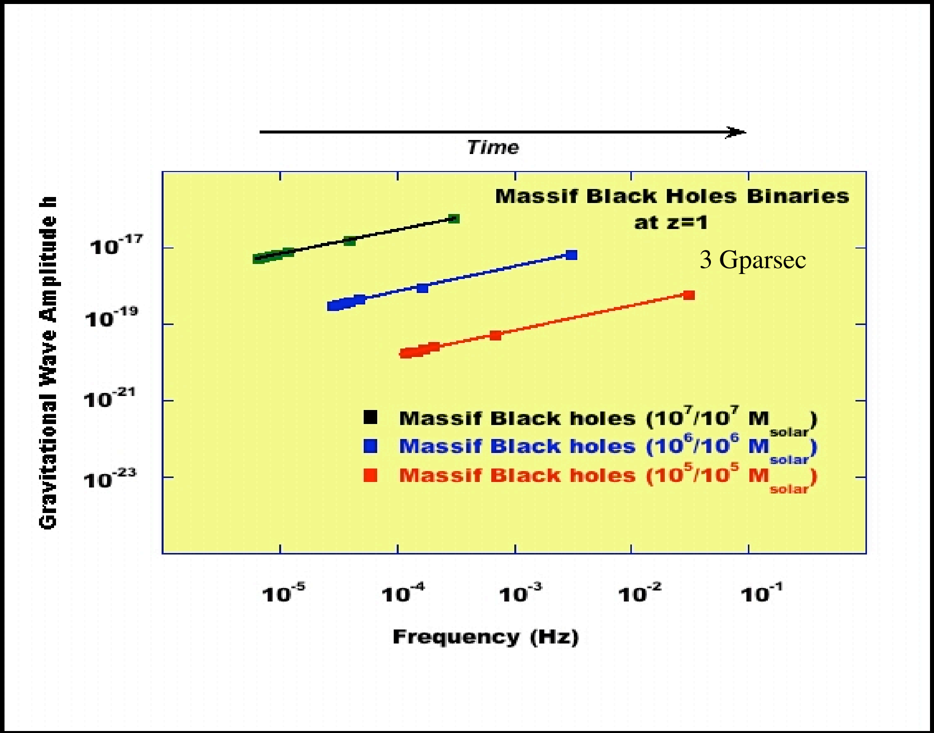
Massive Black Hole cont.



Relativity :

•From inspiraling post-Newtonian waveforms-> precision test of general relativity

- From merger waveforms (numerical relativity) -> test of non linear gravity.

Astrophysics :

- Cosmic history of MBH's-MBH's

Events rates : 0.1 to 100 /years !

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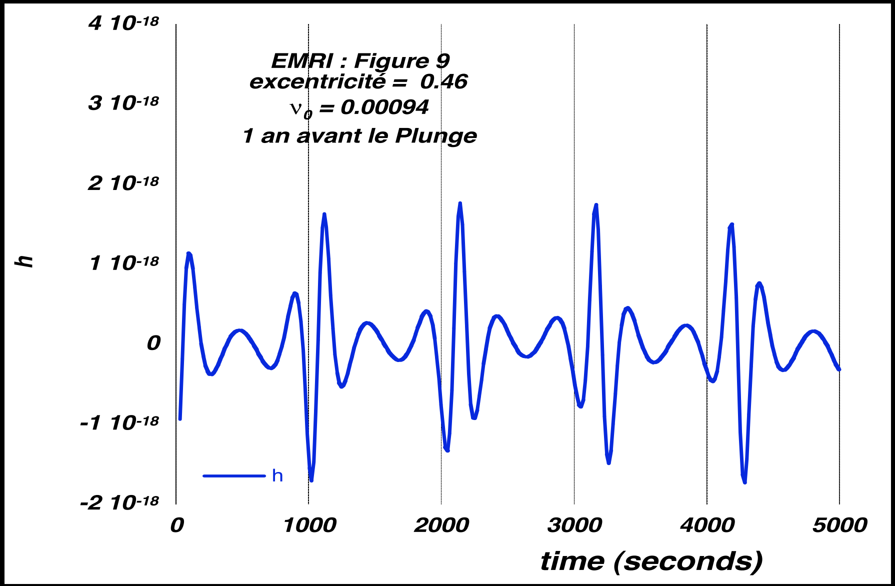
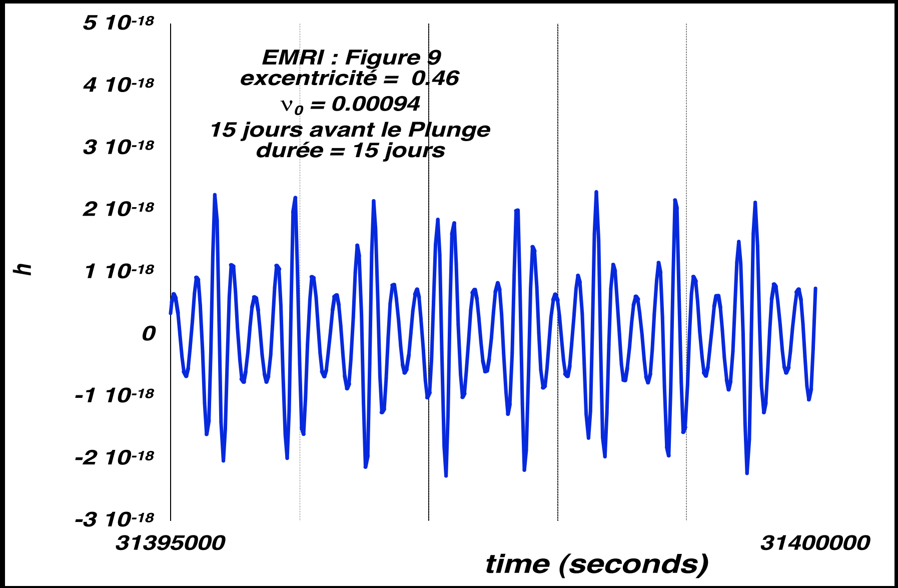
Extreme Mass Ratio in Spiral (EMRI)

Small body spiralling into central body of 10^5 to 10^7 M_{sun}





Relativity :

- Relativistic orbits

Astrophysics :

- Probe astrophysics of dense cluster around MBH's
- Existence and population of IMBH

Events rates/years :

- 500-1000 for $10M_{sun}+10^6M_{sun}$
- 10-90 for $0.6M_{sun}+10^6M_{sun}$
- 1 for $100M_{sun}+10^6M_{sun}$

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Some properties of GW

For the experimentalist ....

- The wave is transverse, it is perpendicular to its direction of propagation.
- The deformation produced by a wave conserves surfaces.
- If the distance between two aligned masses increases, the distance between the two others masses along the perpendicular direction decreases.
- The wave is polarized. H_x *and* H_x
- Important properties : $\frac{\delta L}{L} = \frac{1}{2} h$

Geometrical interpretation of general relativity. L and ∂L should be interpreted as a propre distance. h is indeed a distance

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How to measure

- Six free falling “mirrors”
- Use interferometry for measuring

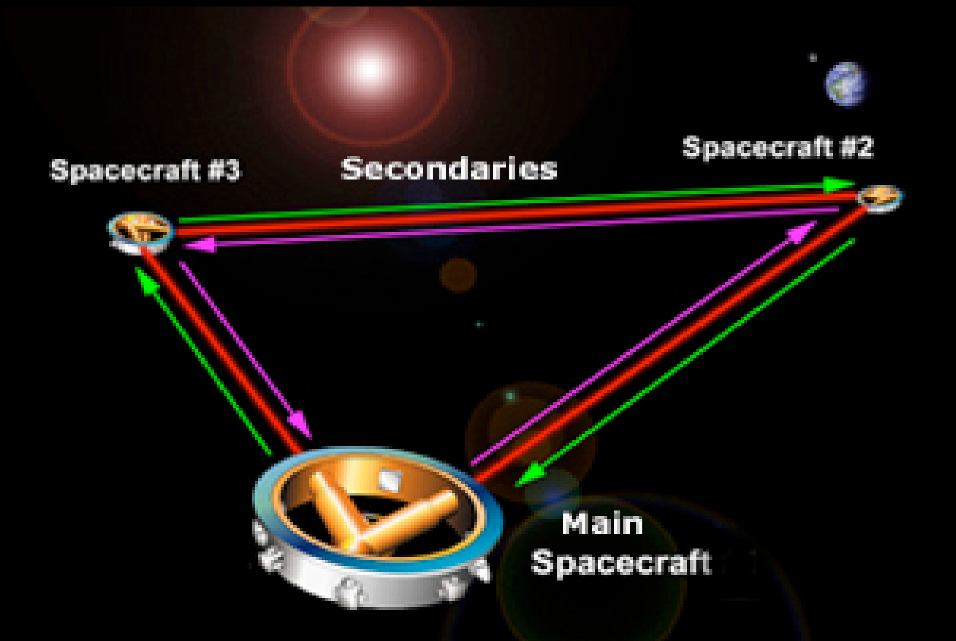
$$\frac{\delta L}{L} = \frac{1}{2} h$$

- LISA frequency band : 10^{-4}-10^{-1} Hertz

$$f = \frac{c}{\lambda} \approx \frac{c}{L}$$

→ $L \approx 5\,10^{6}$ kms

$$\partial L \approx 10^{-12}$$



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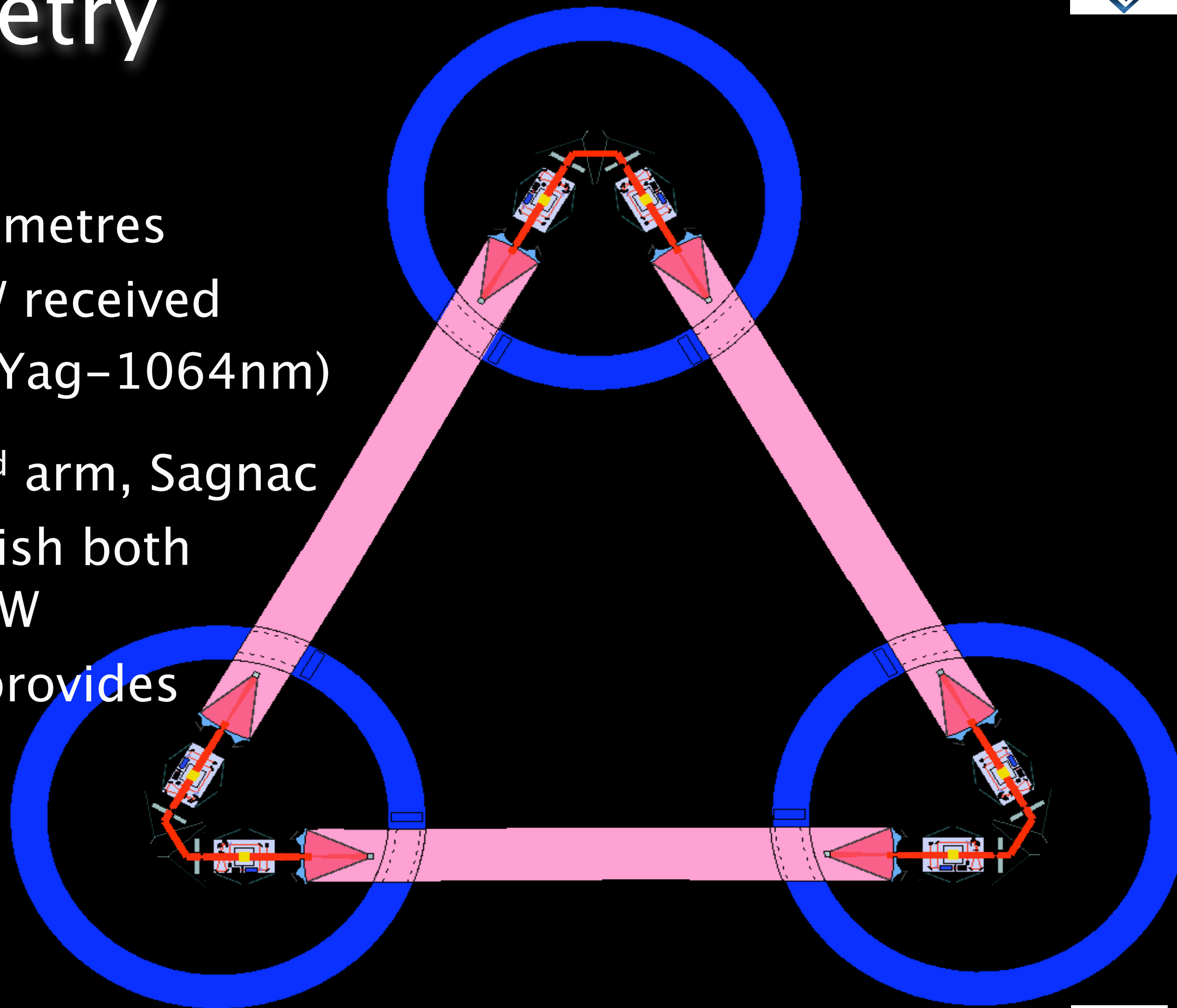
Interferometry

Diffraction widens the laser beam to many kilometres

- 0.7 W sent, 70 pW received
- Need 6 lasers (NdYag-1064nm)

- Michelson with a 3rd arm, Sagnac
- Capable to distinguish both polarizations of a GW
- Orbital movement provides directionality



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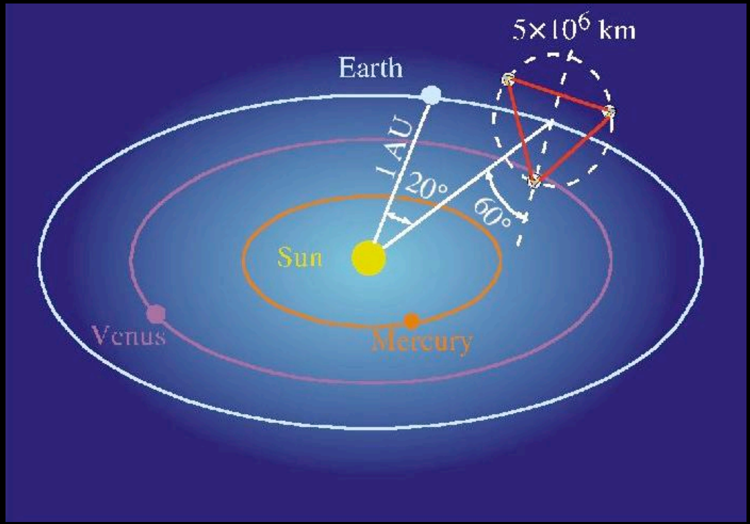
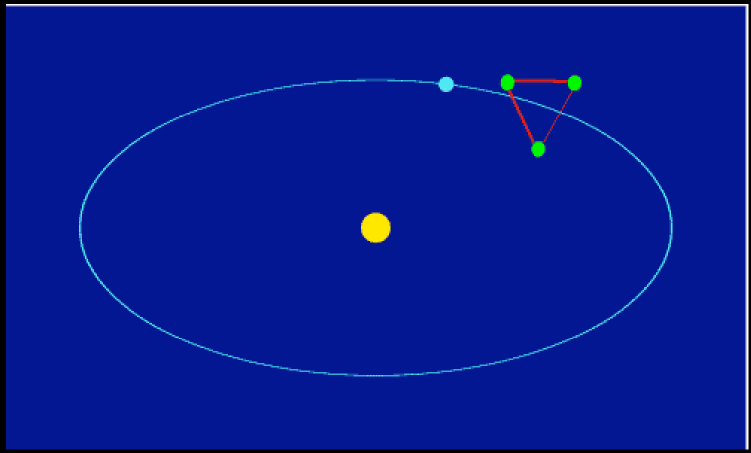
Orbiting

- 3 heliocentric orbits
- LISA centre follow Earth to 20°.
- Angle between LISA frame and ecliptic frame is 60°.
- Variation of LISA during the year

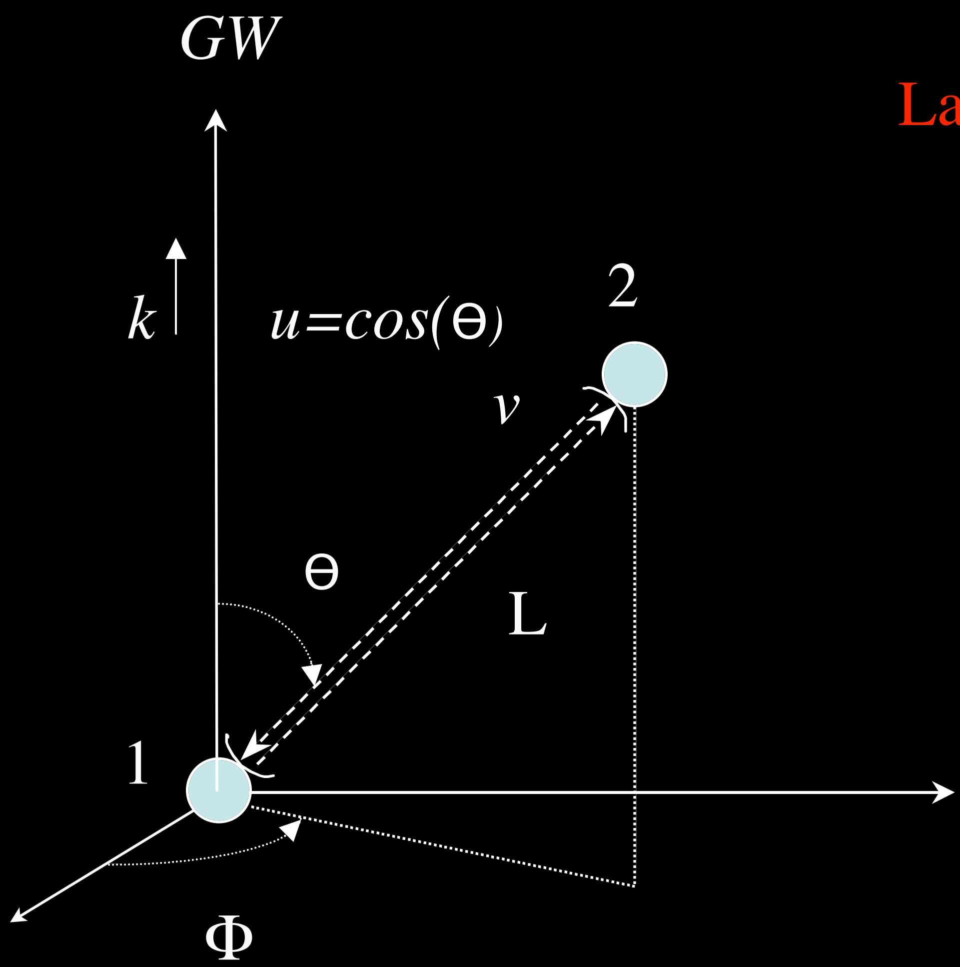
  ⇒Directional information of GWs.

  Multi Michelson ⇒ Polarization of GW





Response function of one arm



Laser frequency

c=1

$$\frac{\Delta\nu(t)}{\nu_0}\Big|_{21}^{GW} = \frac{(1-\mu)}{2}[h(t-(1+\mu)L)-h(t)]$$

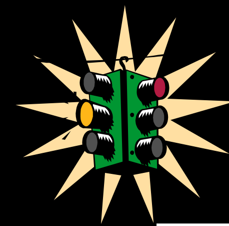
$$\frac{\Delta\nu(t)}{\nu_0}\Big|_{12}^{GW} = \frac{(1+\mu)}{2}[h(t-L)-h(t-\mu L)]$$

$$h(t) \equiv h_+(t)\cos(2\phi) + h_\times(t)\sin(2\phi)$$

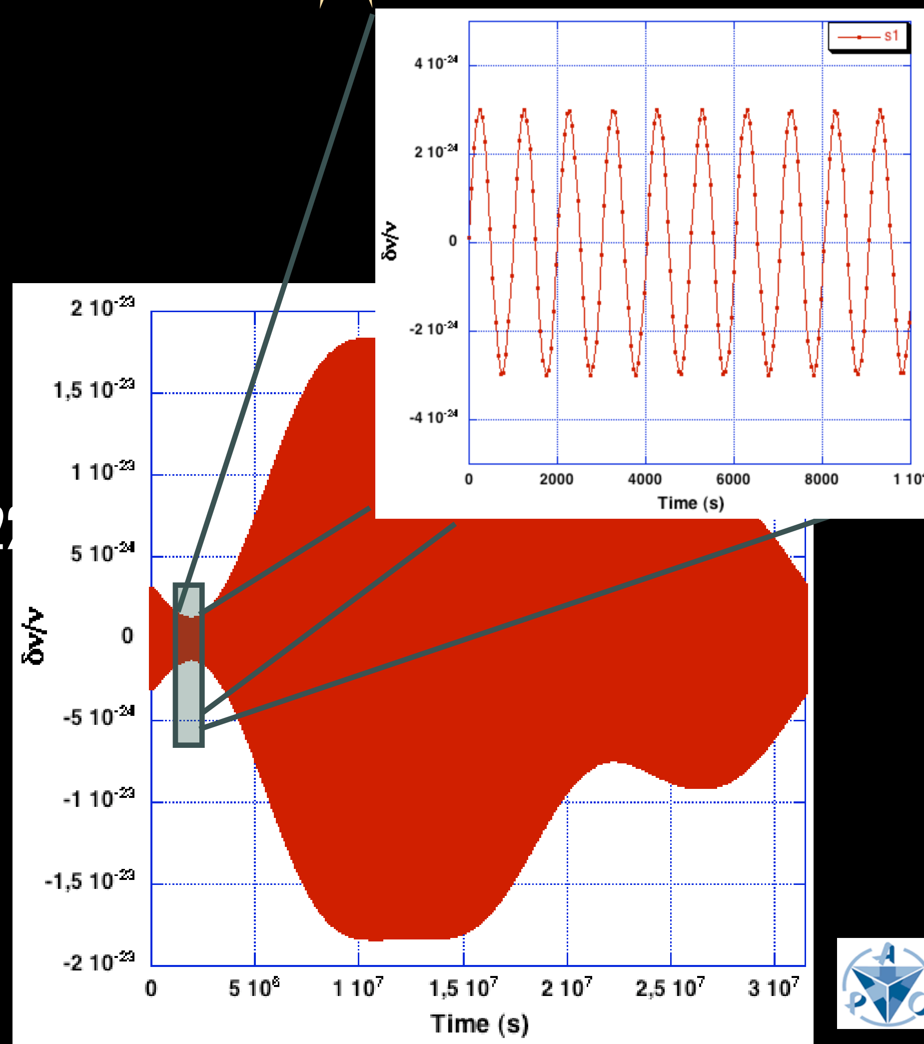
$$\nu(t) = \frac{1}{2\pi}\frac{d\Phi(t)}{dt}$$

Michelson Response of binaries

- $\lambda = 298°$, $\beta = 27°$,
- $\psi = 228°$,
- $f = 10^{-3}$ Hz,
- $h_+ = 3.5\times10^{-22}$, $h_x = 3.5\times10^{-22}$
- $\phi_{0h+} = 4.21$, $\phi_{0hx} = 5.78$.

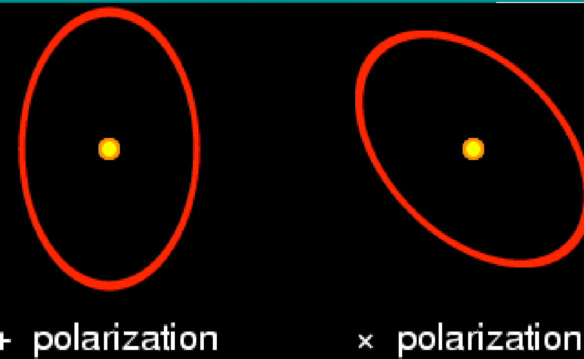


No noise

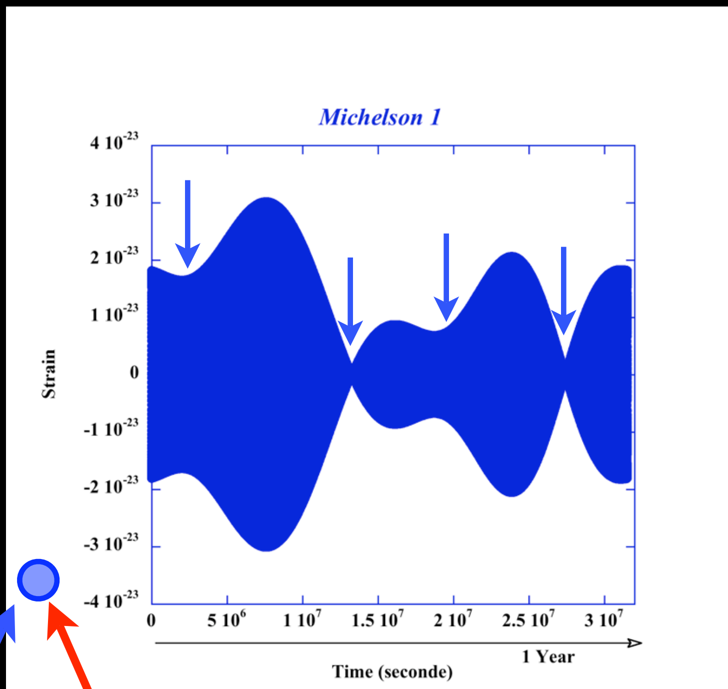


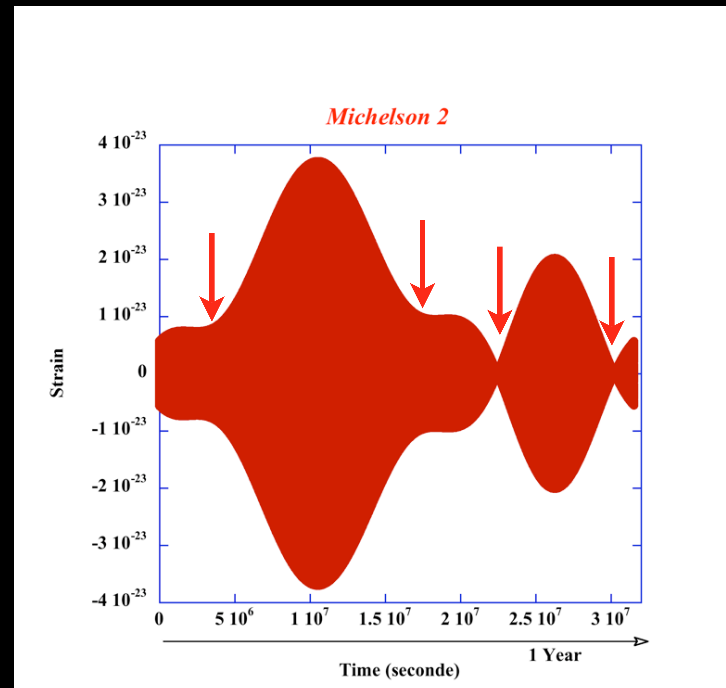
Michelson Response of binaries

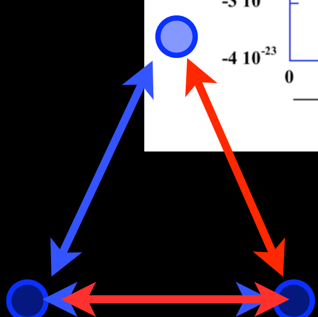
No noise



Monochromatic GW polarization Hx



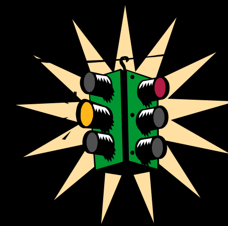




Frequency : 0.0009930348535 Hertz

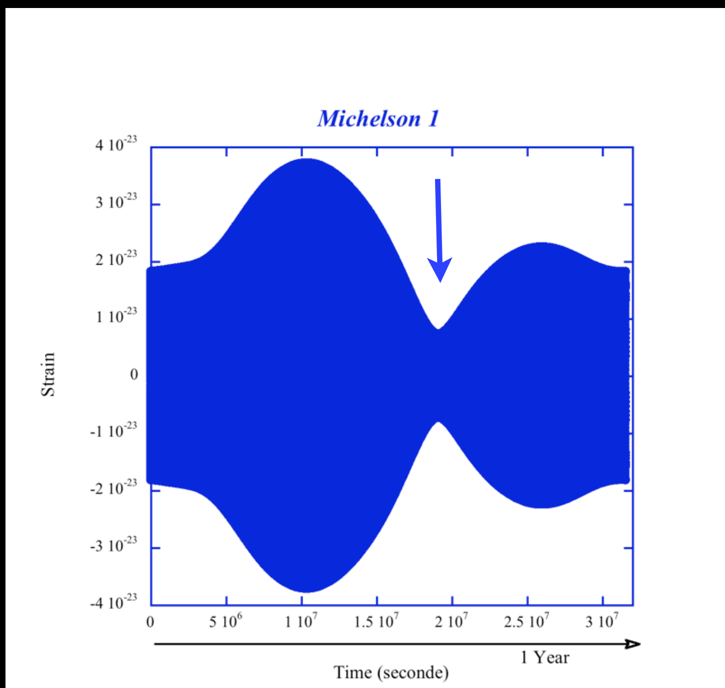
λ : 297.9 β : 27.16

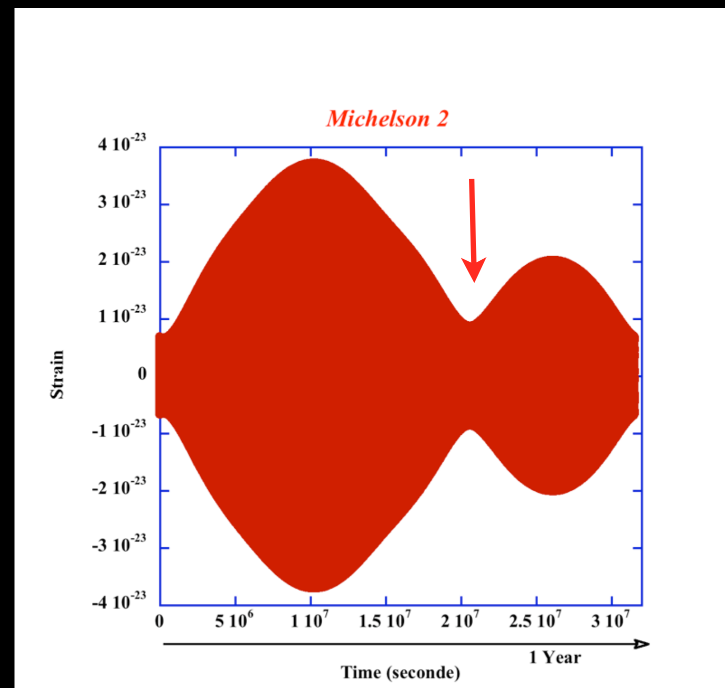
Michelson Response of binaries



No noise

Monochromatic GW polarization H+,Hx

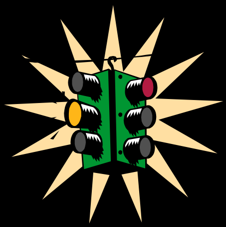




Frequency : 0.0009930348535 Hertz

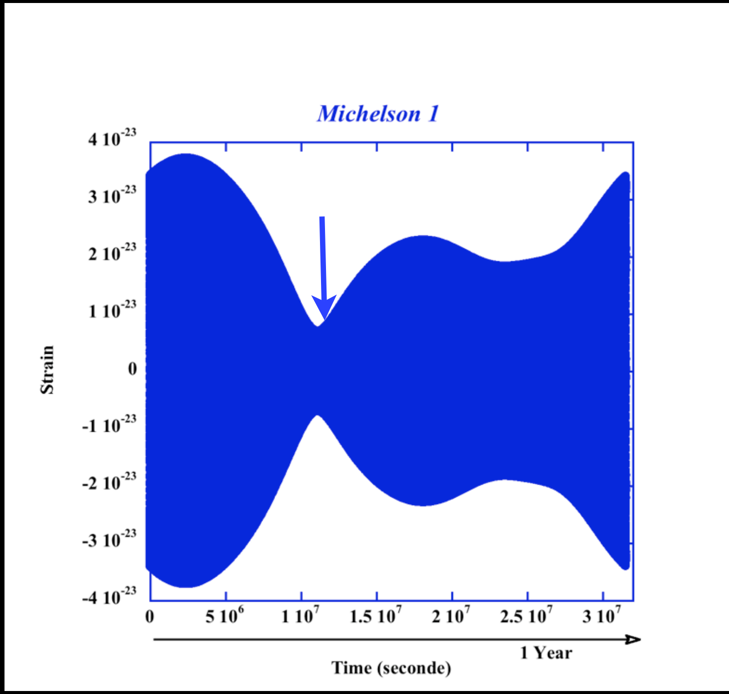
λ : 297.9 β : 27.16

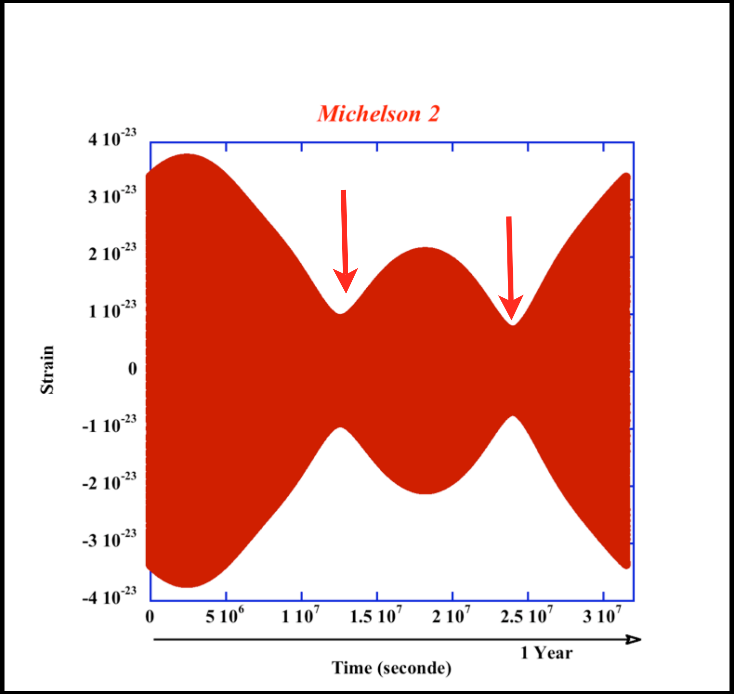
Michelson Response of binaries



No noise

Monochromatic GW same polarization





Frequency : 0.0009930348535 Hertz

λ : +90 β : +90

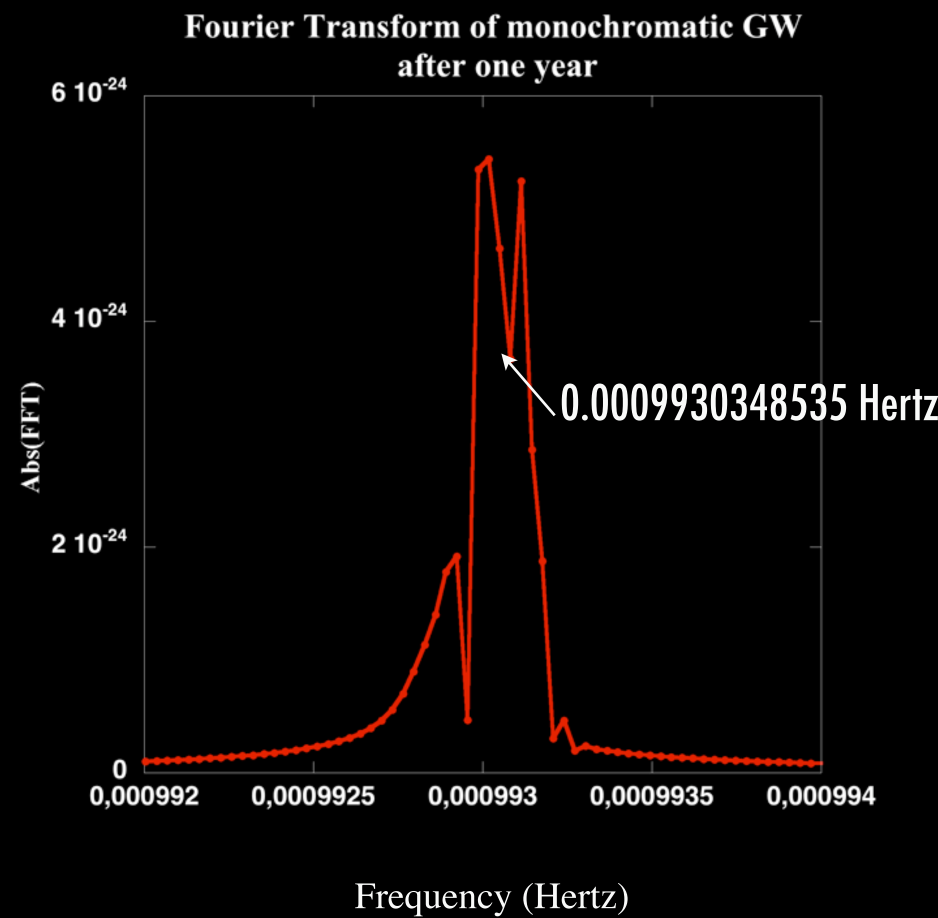
Frequency response

- Modulation
- Doppler shift

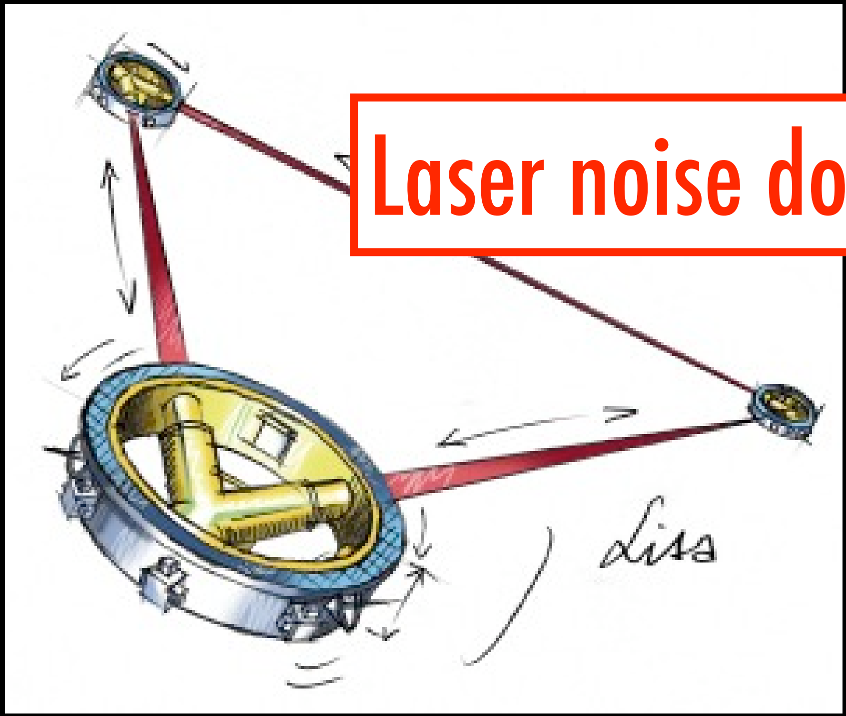
Frequency : 0.0009930348535 Hertz

λ : 297.9 β : 27.16

No noise



LISA : Noises



Laser noise : Interference between two lasers which are not perfectly stable.

30 Hz.Hz$^{-1/2}$

t)

Laser noise dominates the signal

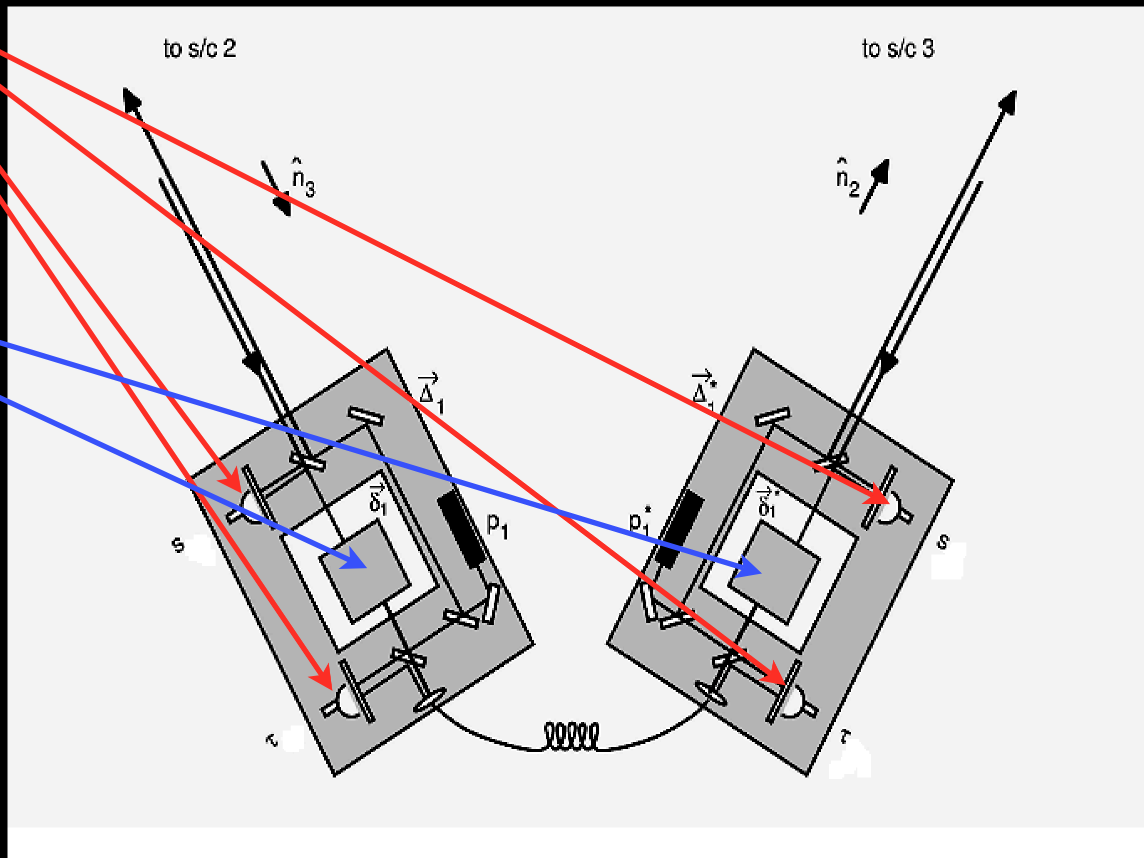
Inertial masses Imperfection of drag free system.

Shot Noise Measurement noise on the photodiode

Laser noise

- By spacecraft 4 measurements

2 "mirrors"
inertial masses



Laser noise T.D.I (Time Delay Interferometry)

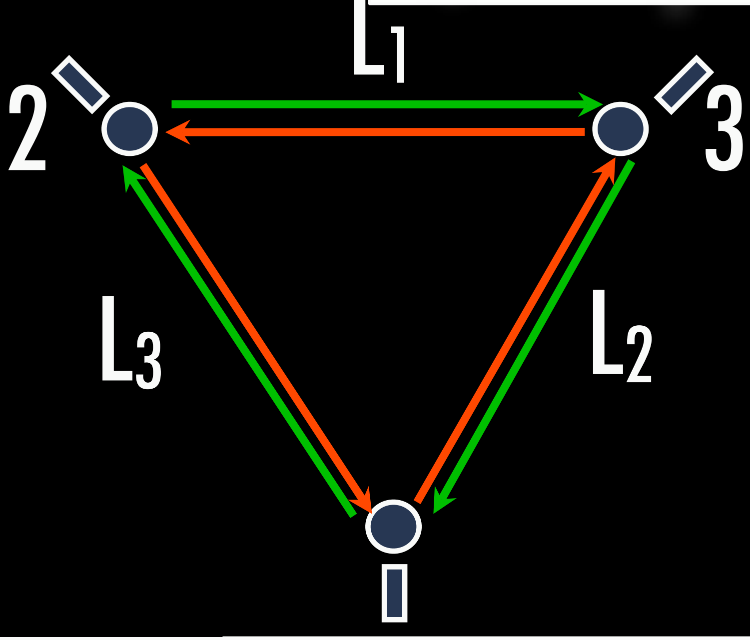
numerical interferometry

Laser frequency

$$\frac{\Delta\nu(t)}{\nu_0}\Big|_{21}^{GW} = \frac{(1-\mu)}{2}[h(t-(1+\mu)L)-h(t)]$$

$$\frac{\Delta\nu(t)}{\nu_0}\Big|_{12}^{GW} = \frac{(1+\mu)}{2}[h(t-L)-h(t-\mu L)]$$

of LISA as a closed array delay lines between the test masses.



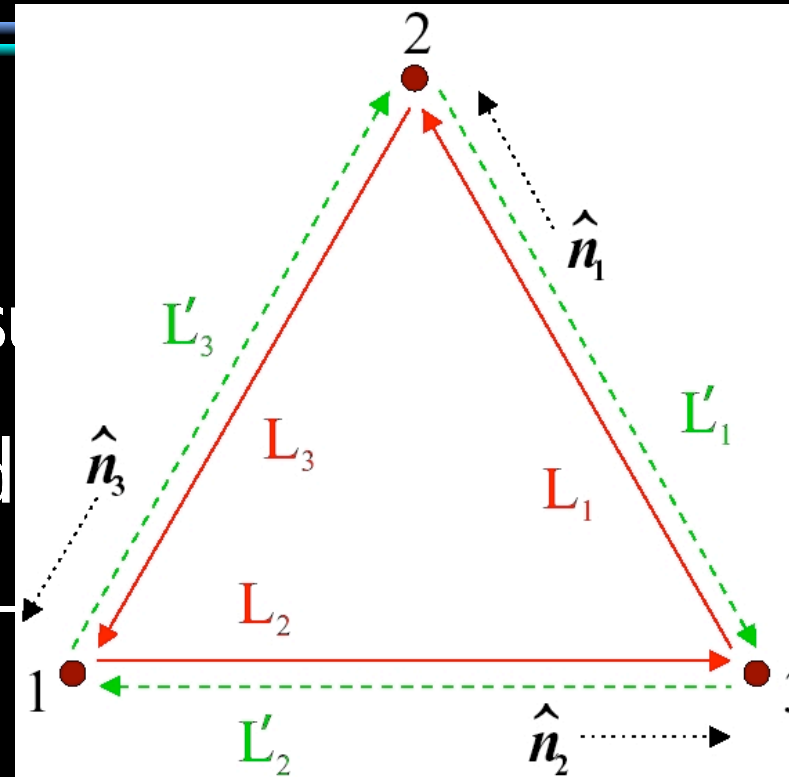
This approach allows us to reconstruct the unequal-arm Michelson interferometer, as well as new interferometric combinations, which offer advantages in hardware design, in robustness to failures of single links, and in redundancy of data.

$$D = (t - \frac{L}{c})$$

$$\alpha = s_1 + D_3 s_2 + D_3 D_1 s_3 - (s_1' + D_2 s_3' + D_2 D_1 s_2') = 0$$

Laser noise T.D.I

- Phase shift between the two beams meas
- Beams from an external spacecraft, are d
  - delay operator D_i : $D_i\, x(t) = x(t-L$
- The measurements :



$$s_1 = s_1^{GW} + s_1^{ShotNoise} + D_3 p'_2 - p_1 + \nu_0 \left(-2.\hat{n}_3.\vec{\delta}_1 + \hat{n}_3 \vec{\Delta}_1 + \hat{n}_3.D'_3 \vec{\Delta}'_2 \right)$$

$$\tau_1 = p'_1 - p_1 - 2\nu_0 \hat{n}_2. \left(\vec{\delta}'_1 - \vec{\Delta}'_1 \right) + \mu_1$$

$$s'_1 = {s'}_1^{GW} + {s'}_1^{ShotNoise} + D'_2 p_3 - p'_1 + \nu_0 \left(2.\hat{n}_2.\vec{\delta}'_1 - \hat{n}_2.\vec{\Delta}'_1 - \hat{n}_2.D_2 \vec{\Delta}_3 \right)$$

$$\tau'_1 = p_1 - p'_1 + 2\nu_0 \hat{n}_3. \left(\vec{\delta}_1 - \vec{\Delta}_1 \right) + \mu_1$$

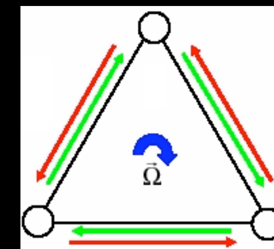
With only the laser noise :

$$s_1 = s_1^{GW} + D_3 p'_2 - p_1$$

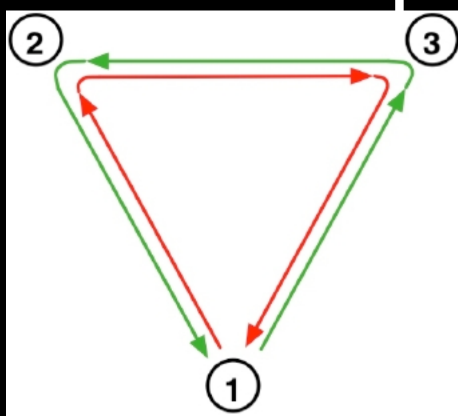
$$s'_1 = {s'}_1^{GW} + D'_2 p_3 - p'_1$$

Laser noise T.D.I

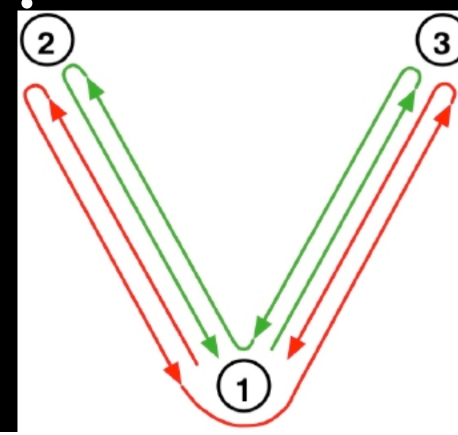
- Many groups of TDI generators
  - 1^{st} generation : fixed LISA configuration.
  - 2^{nd} generation : consideration of flexing and Sagnac effect.



- Geometric representation by beam loops :



$$\begin{aligned}\alpha &= -s_1 - D_3\, s_2 - D_1 D_3\, s_3 \\ &\quad + s'_1 + D_{2'}\, s'_3 + D_{1'}\, D_{2'}\, s'_2 \\ &\simeq 0\end{aligned}$$



$$\begin{aligned}X &= -s_1 - D_3\, s'_2 - D_3 D_{3'}\, s'_1 - D_3 D_{3'} D_{2'}\, s_3 \\ &\quad + s'_1 + D_{2'}\, s_3 - D_{2'} D_2\, s_1 - D_{2'} D_2 D_3\, s_3 \\ &\simeq 0\end{aligned}$$

Laser noise T.D.I

- In summary: there are 6 optical benches, 6 lasers, and a total of 12 Doppler time series observed.
- The 6 beams exchanged between distant spacecraft contain the information about the GW signal (s_{ij}); the other 6 signals (t_{ij}) are for comparison of the lasers and relative optical bench motions within the spacecraft.
- The functional space of interferometric combinations can be generated with the 4 generators α, β, γ, ξ

$$\zeta - \zeta_{,123} = \alpha_{,1} - \alpha_{,23} + \beta_{,2} - \beta_{,31} + \gamma_{,3} - \gamma_{,12}$$

$$X_{,1} = \alpha_{,32} - \beta_{,2} - \gamma_{,3} + \zeta$$

$$P = \zeta - \alpha_{,1}$$

$$E = \alpha_{,1} - \zeta_{,1}$$

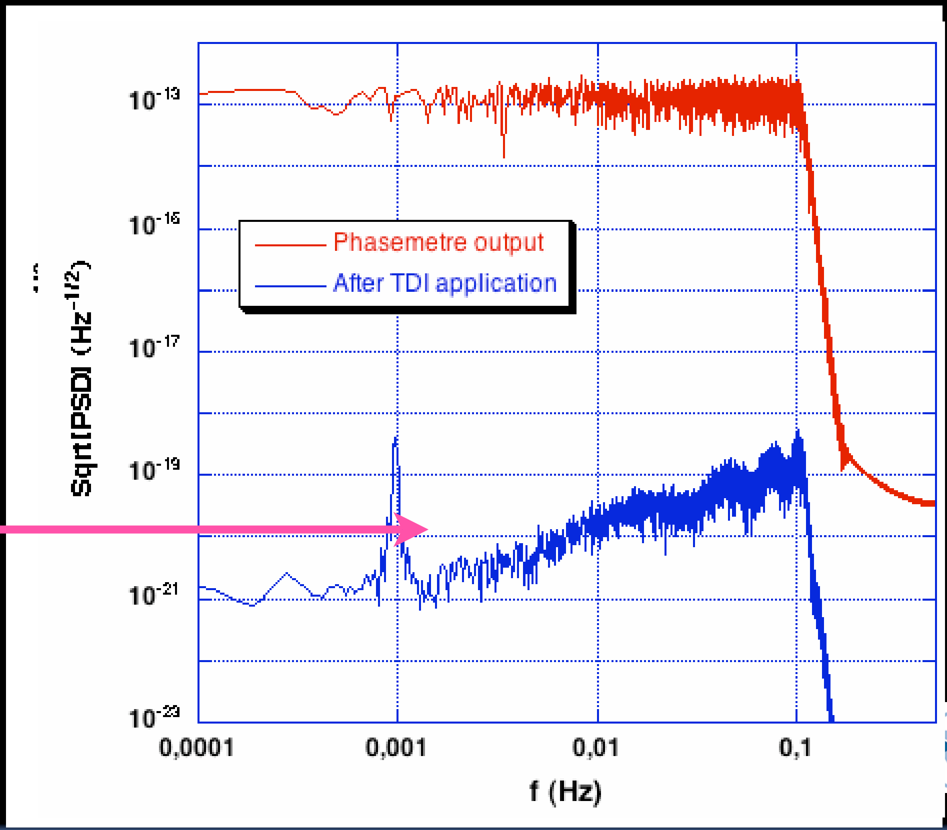
$$U = \gamma_{,1} - \beta$$

Laser noise T.D.I

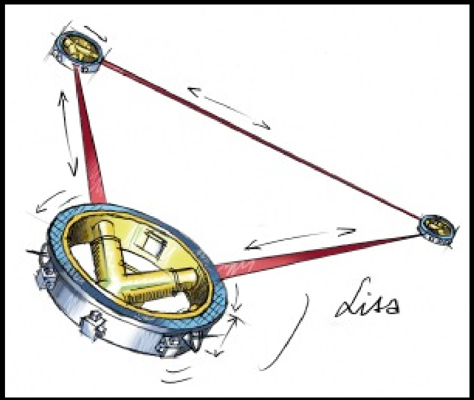
- The laser noise is modeled by a bandwidth limited white noise at 30 $Hz.Hz^{-1/2}$.
- The application of TDI recovers the GW signal.

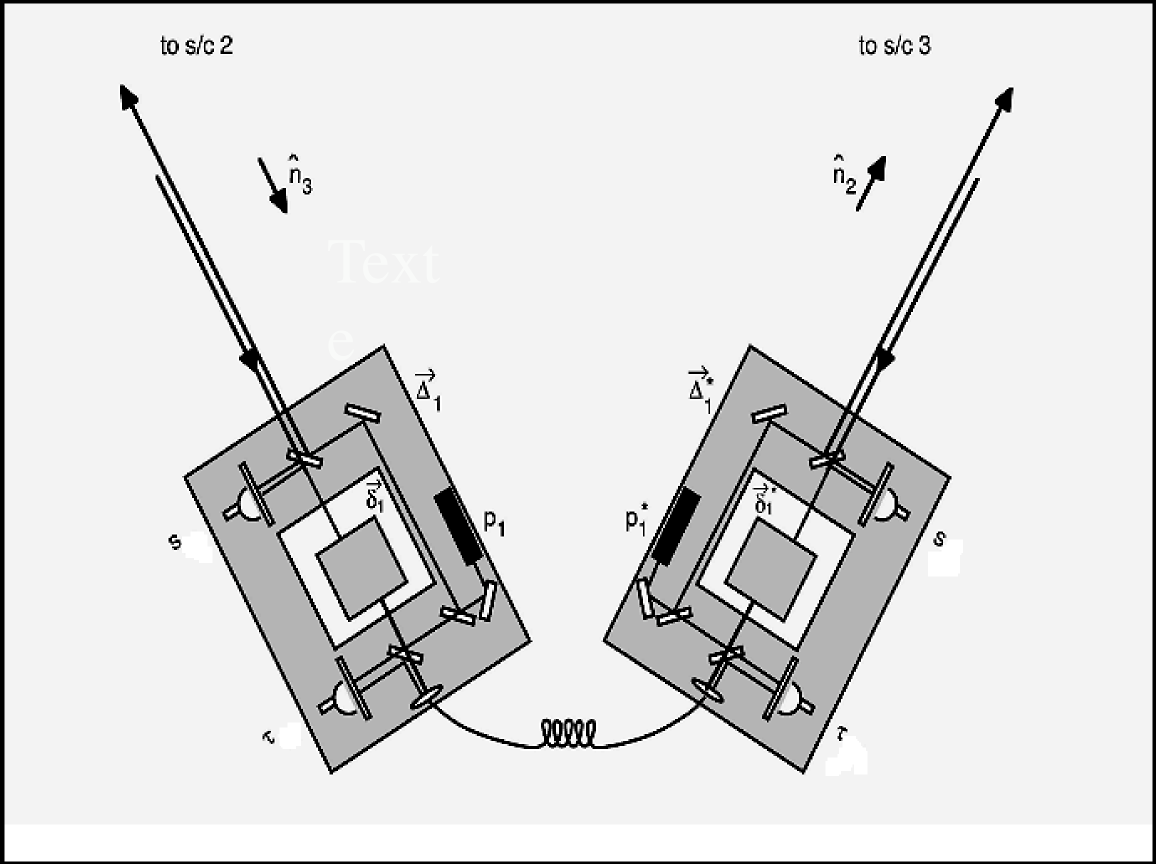
A Gw is hidden in there !

Here it is !



Inertial masses

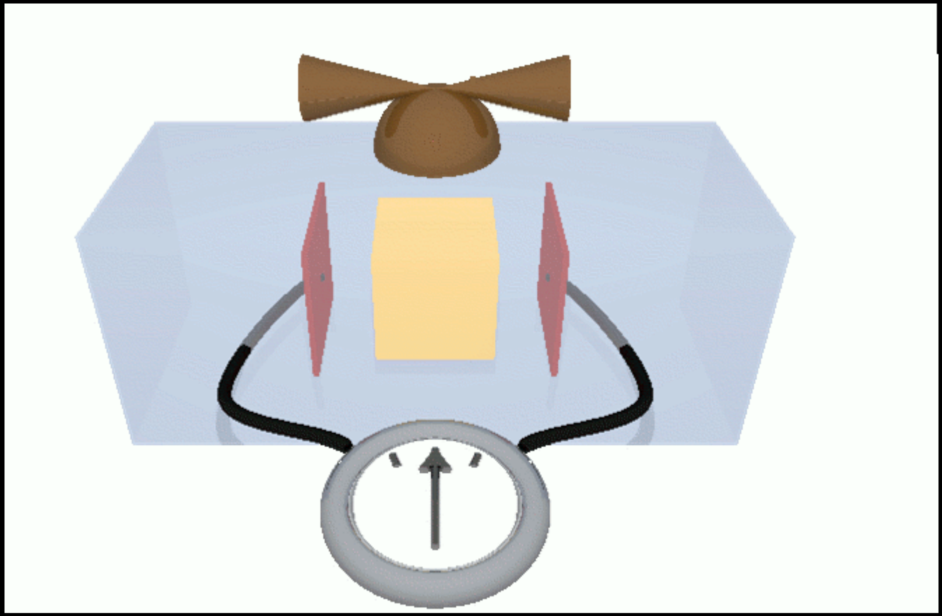


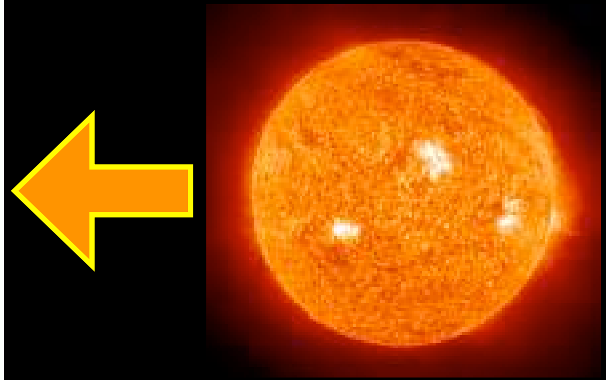


♚ Inertial masses

Free Fall in Space

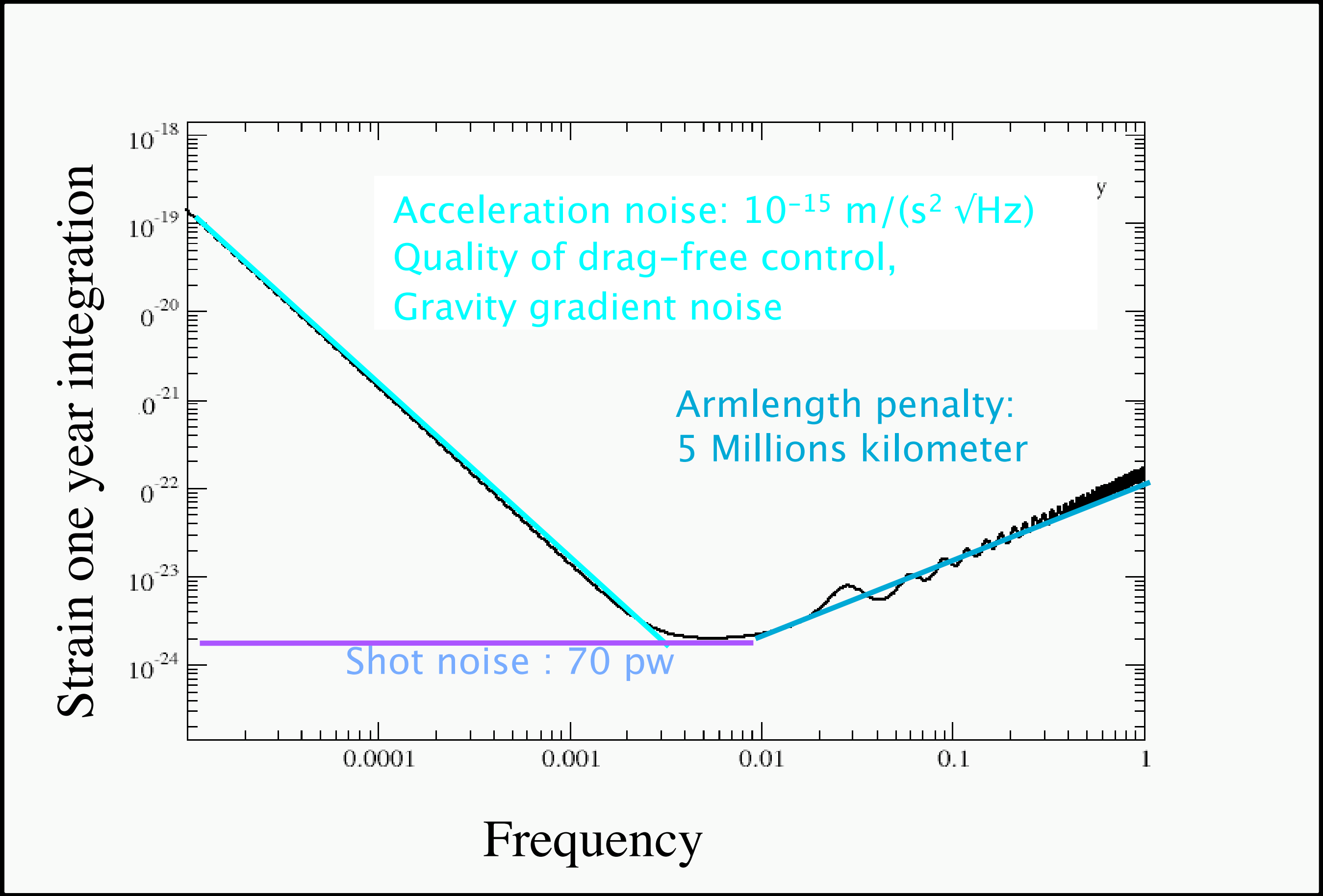
Drag free control





The resulting motion of the solar wind would be 10^4 times larger than the tiny motion due to GW

Noise Limitation



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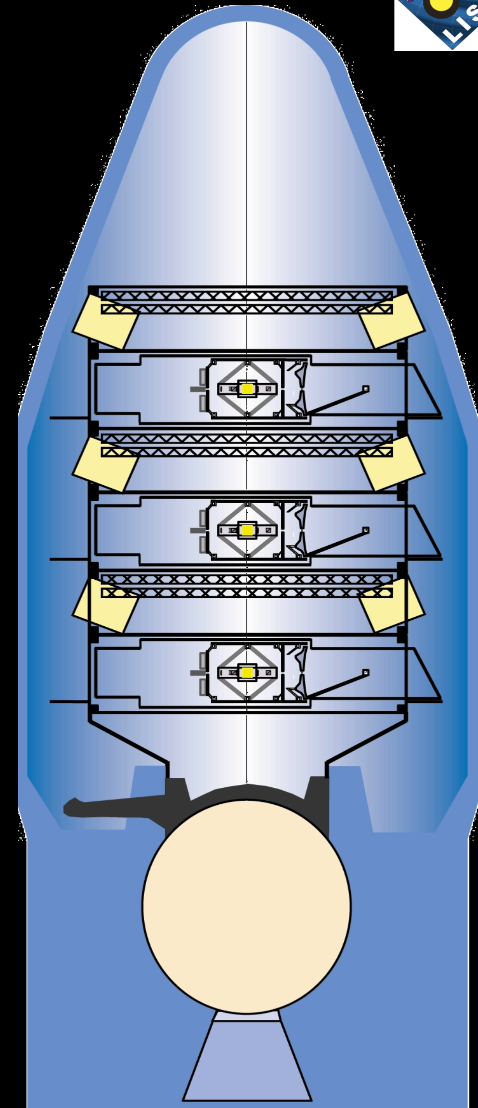
Summary

- Proposed to ESA 1993, approved as a Cornerstone Mission 1996
- Collaborative ESA/NASA mission with a 50/50 sharing ratio
  - ESA: Responsibility for the payload I&T, 50% of the payload (nationally funded)
  - NASA: 3 S/C, launcher, ground segment (DSN), mission ops
  - Science ops will be shared
  - Data analysis by two independent teams (Europe and US)
- Launch foreseen in the 2014/??? timeframe



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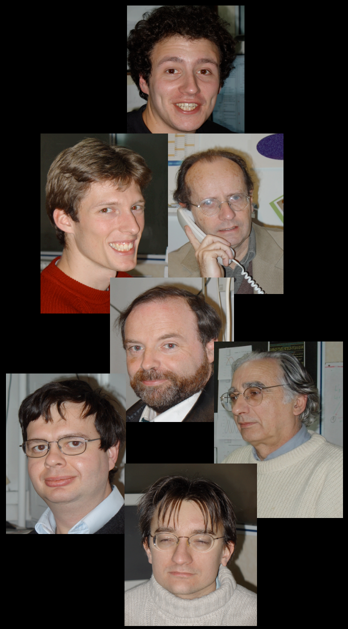
Team LISA APC



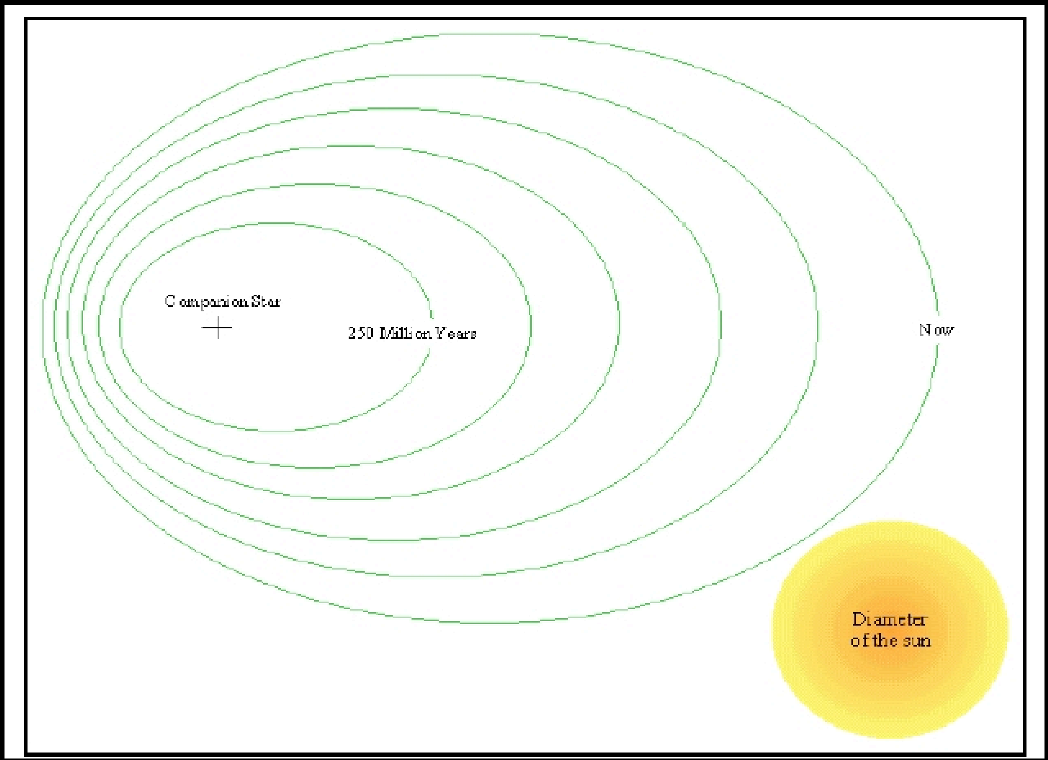
• Contribution to the interferometry of LISA Pathfinder.
• Development of a simulator for the LISA mission (LISA Code).
•R&D in Laser frequency stabilization (Iodine molecular line)

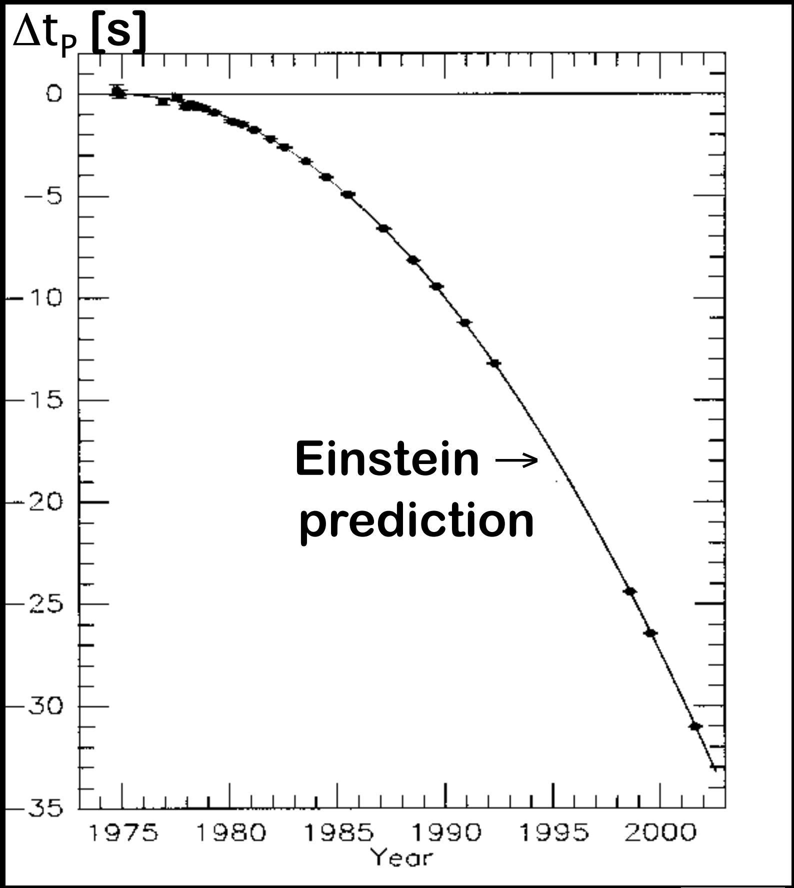
http://www.srl.caltech.edu/lisa/documents/PrePhaseA.pdf

http://www.apc.univ-paris7.fr/LISA-France/biblio.phtml

End

Indirect proof





Hulse-Taylor Binary PSR1913+16 (1974)
Nobel Price (1993)

Remark : Outside of LISA

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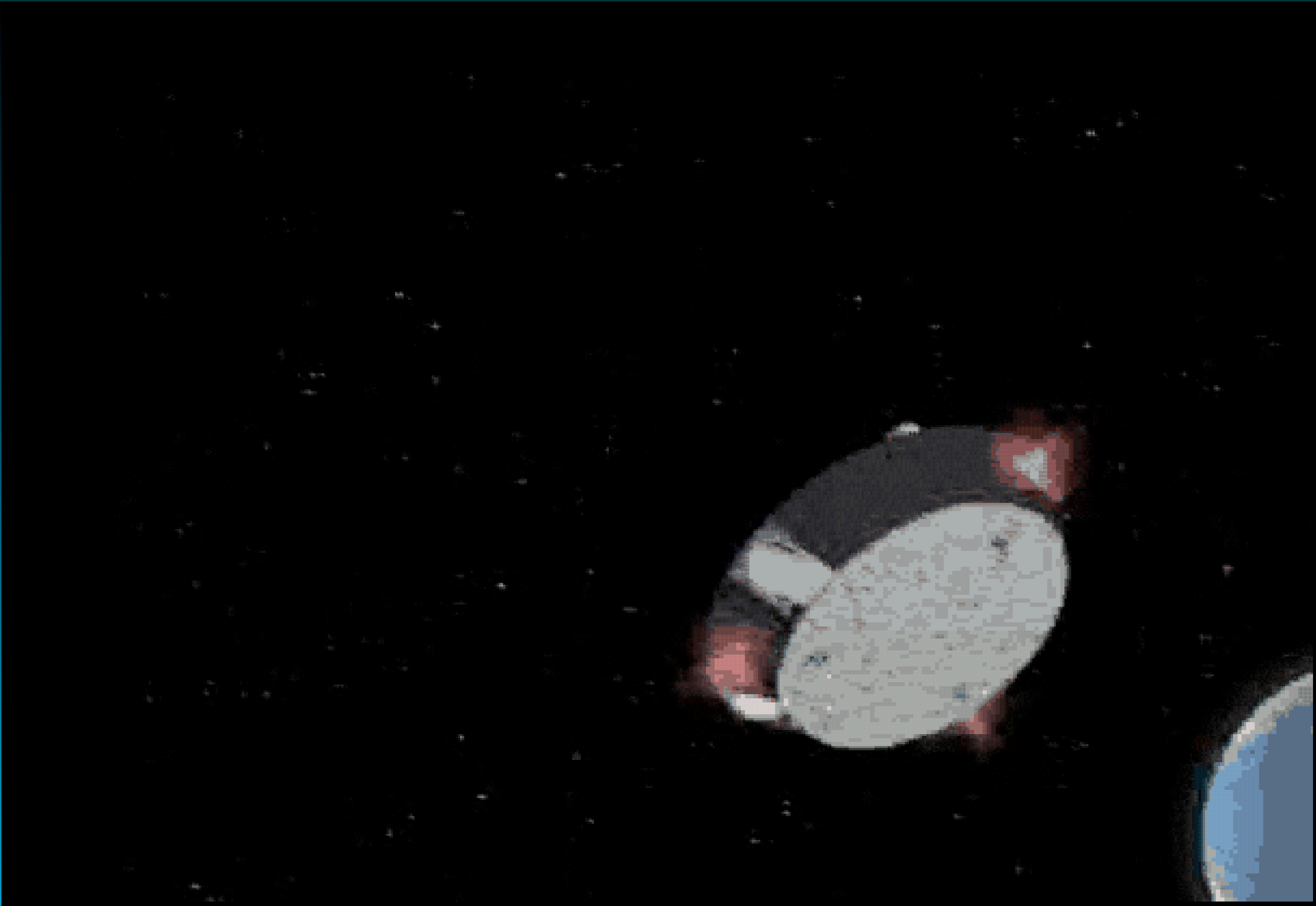

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