SAGE : Can we detect gravitational waves with CubeSats?

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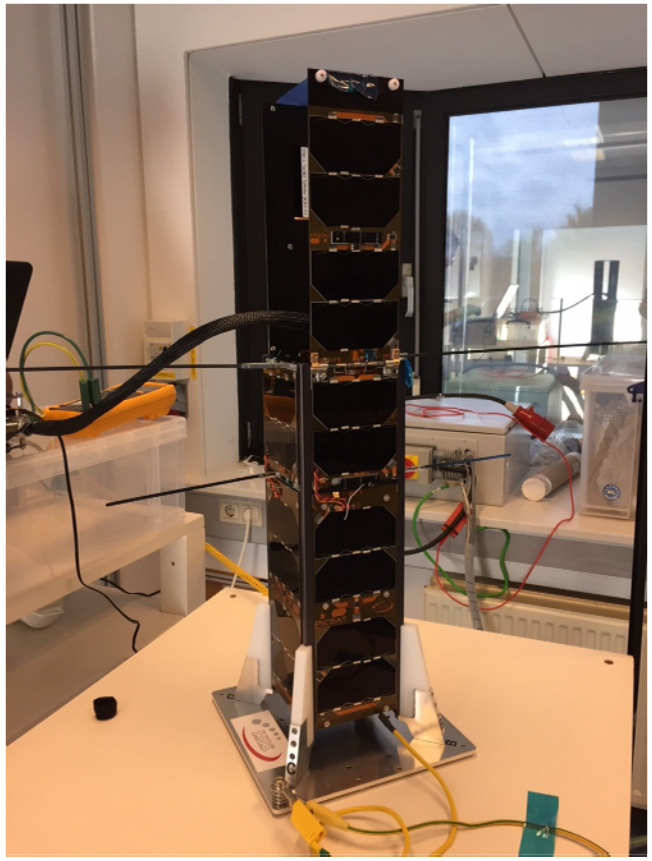
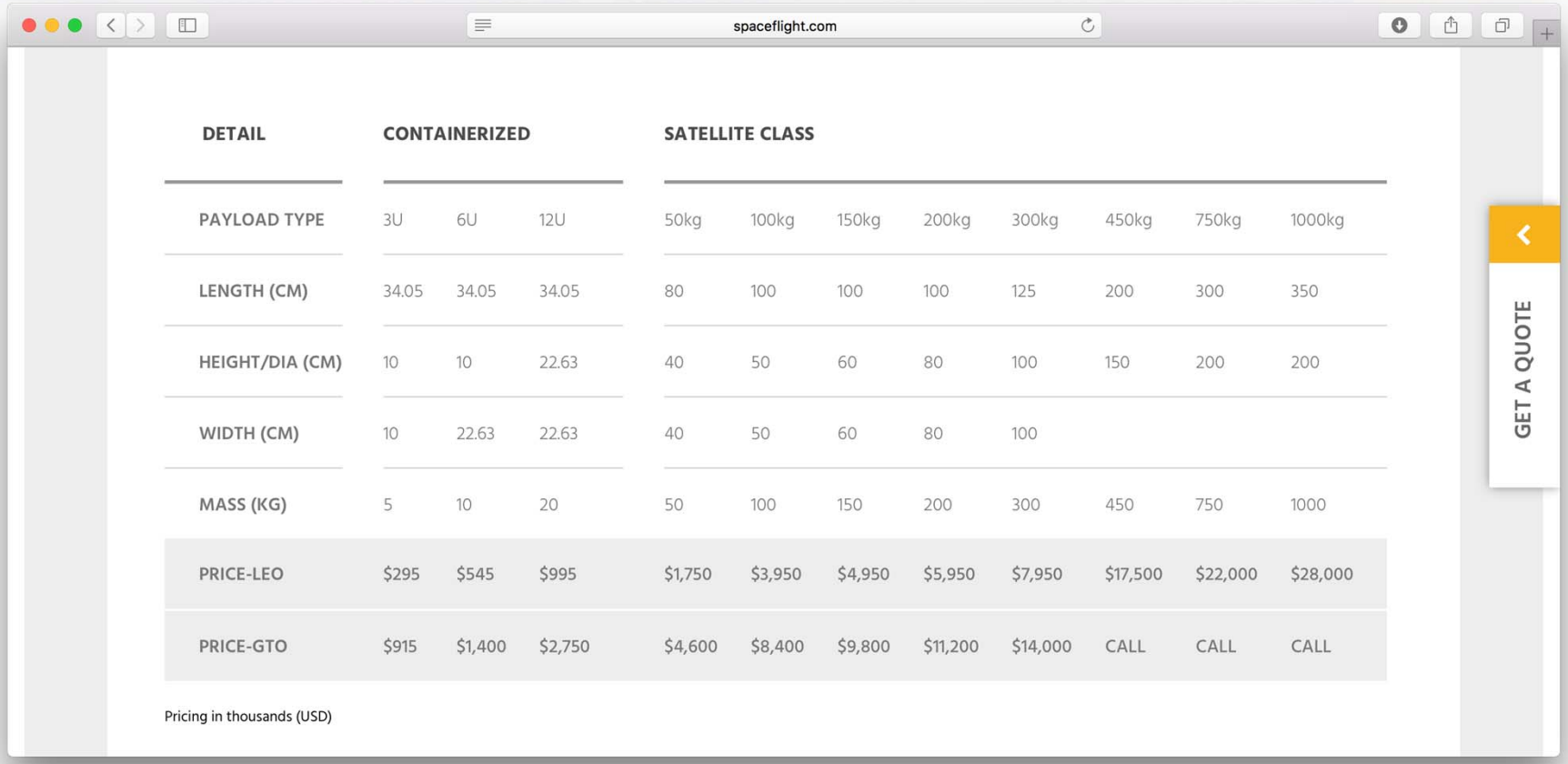
PICSAT

- Photometer 100ppm
- Technology demonstrator for single mode fibre
- Development started Mach 2015
- Launched January 2018 on PSLV C-40
- Lost contact in Mars 2018



Pricing



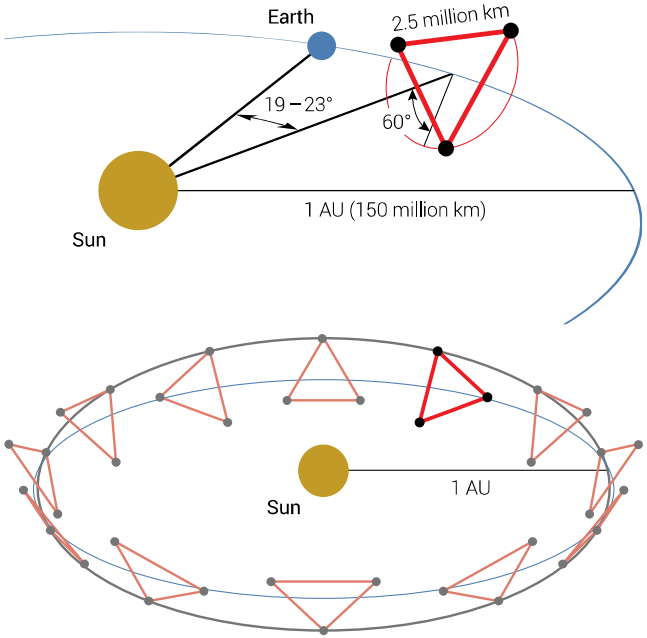
DETAIL	CONTAINERIZED			SATELLITE CLASS							
PAYLOAD TYPE	3U	6U	12U	50kg	100kg	150kg	200kg	300kg	450kg	750kg	1000kg
LENGTH (CM)	34.05	34.05	34.05	80	100	100	100	125	200	300	350
HEIGHT/DIA (CM)	10	10	22.63	40	50	60	80	100	150	200	200
WIDTH (CM)	10	22.63	22.63	40	50	60	80	100			
MASS (KG)	5	10	20	50	100	150	200	300	450	750	1000
PRICE-LEO	$295	$545	$995	$1,750	$3,950	$4,950	$5,950	$7,950	$17,500	$22,000	$28,000
PRICE-GTO	$915	$1,400	$2,750	$4,600	$8,400	$9,800	$11,200	$14,000	CALL	CALL	CALL

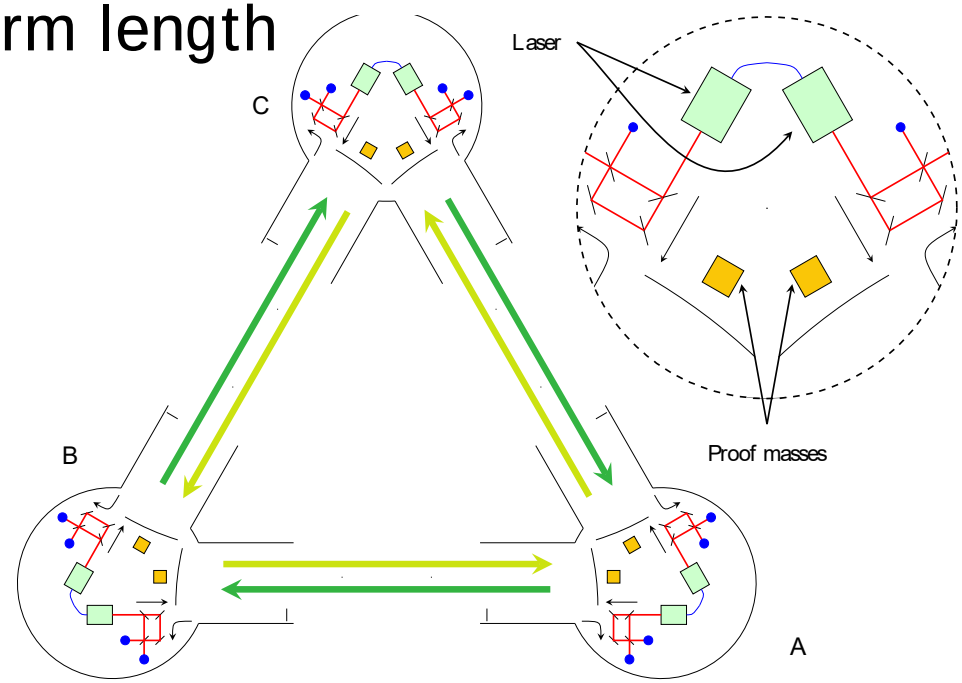
Pricing in thousands (USD)

GET A QUOTE

LISA

- Michelson interferometer in space
- 2.5 millions kilometers arm length

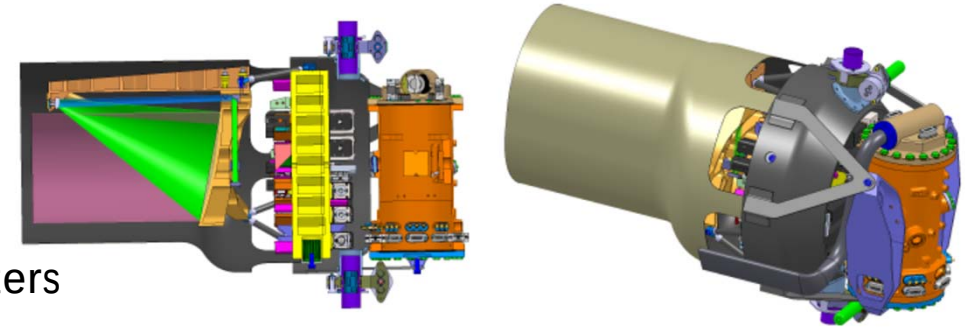




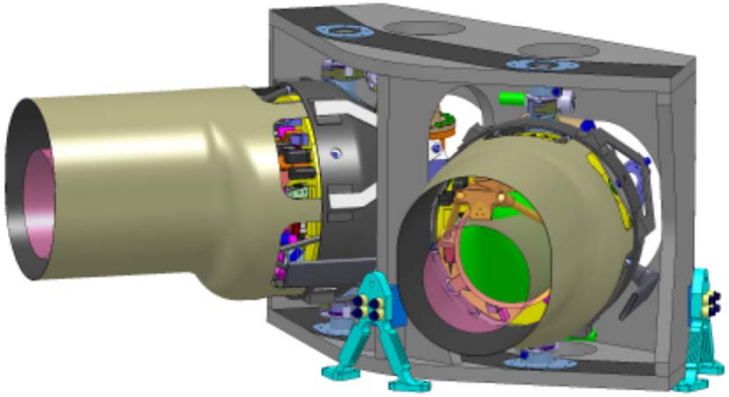
From LISA White Book 2017

LISA

- 2 off axis telescopes 30cm
- 2 optical bench with bulk interferometers



- 2 accelerometer (5 centimeters cubes)
- 1 Disturbance Reduction System (thrusters)
- Thermal stability !



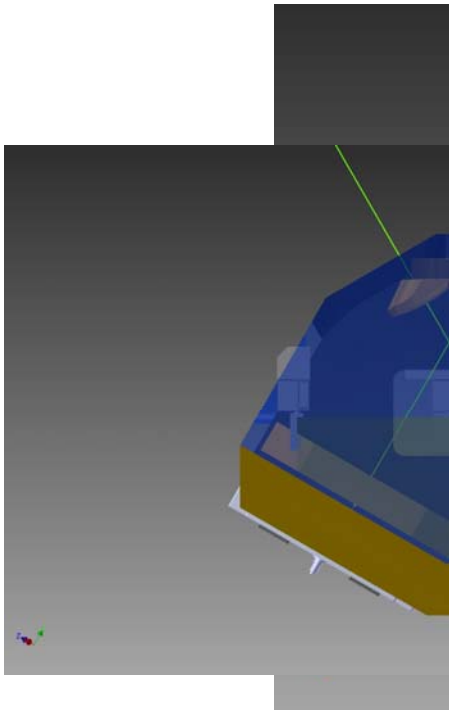
LISA = > SAGE

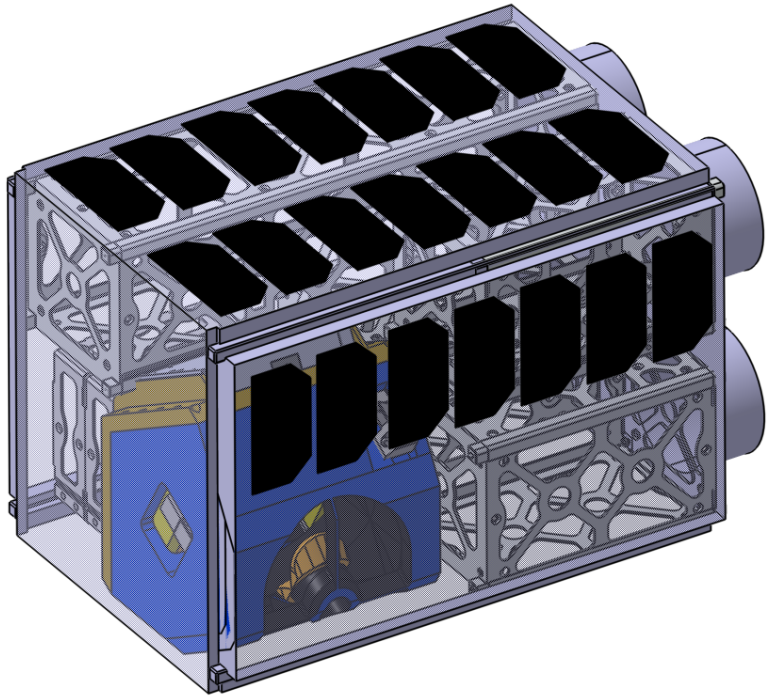
- 2 off axis telescopes 30cm => 10cm mirrors
- 2 optical bench with bulk interferometers => Fibered interferometry

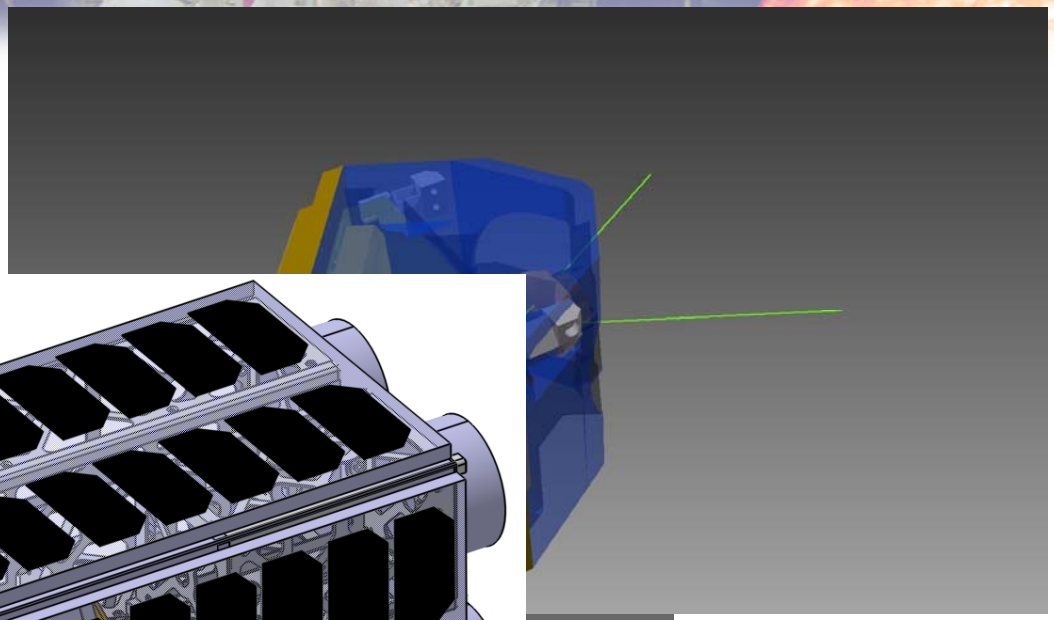
- 2 accelerometer (5 centimeters cubes)
- 1 Disturbance Reduction System (thrusters)
- Thermal stability ! => 100mW laser beam only

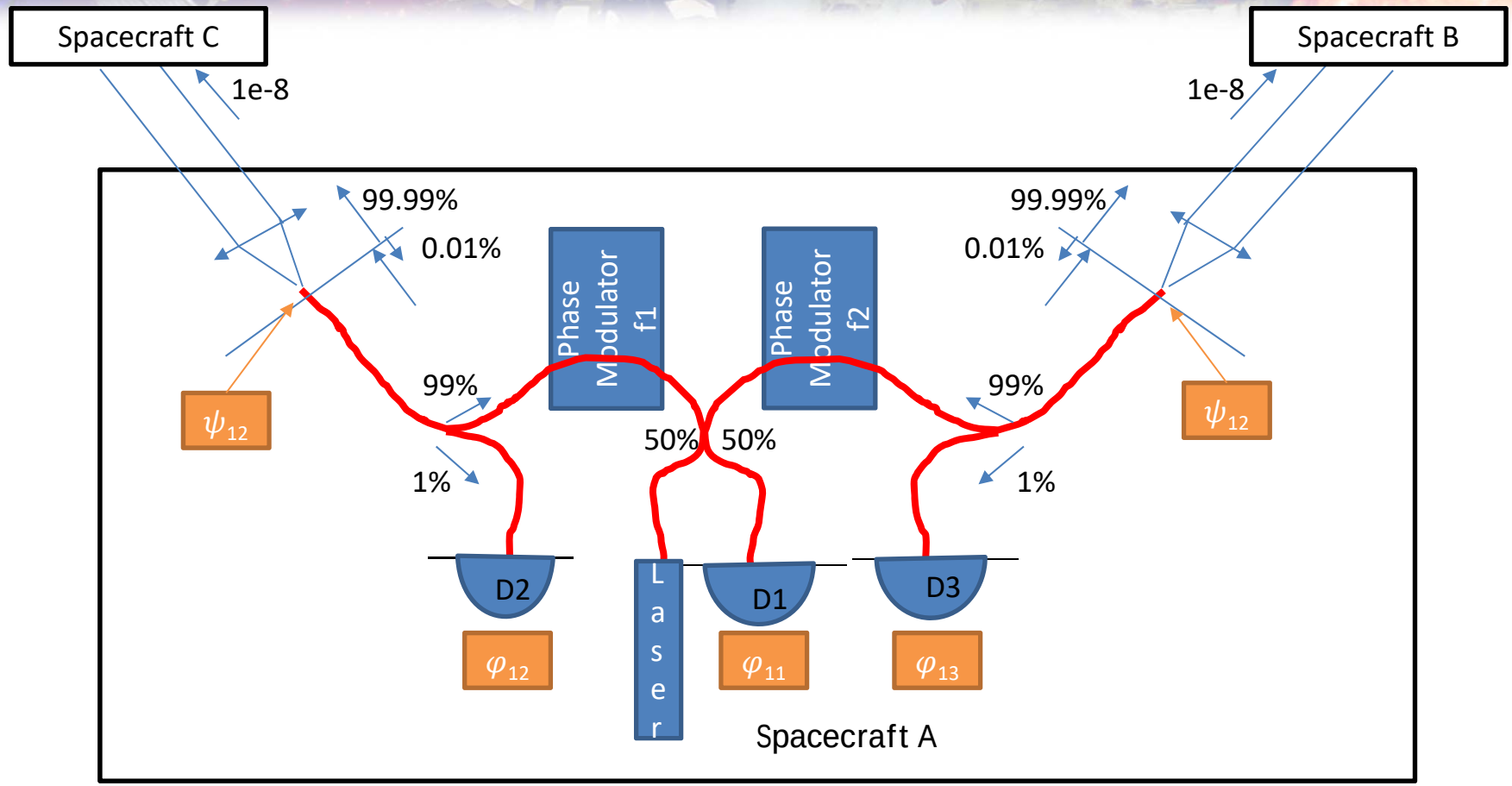
SAGE

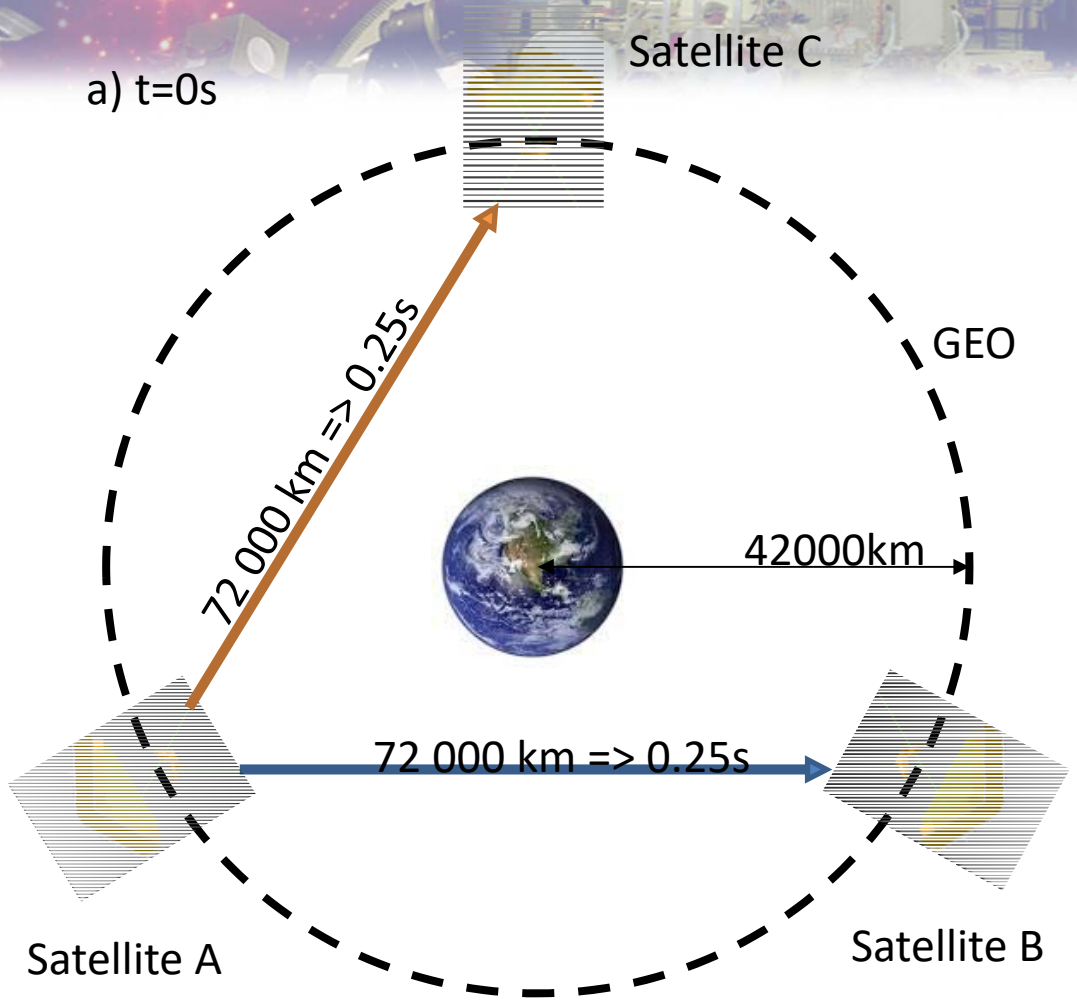
- 60° intertwined telescopes:

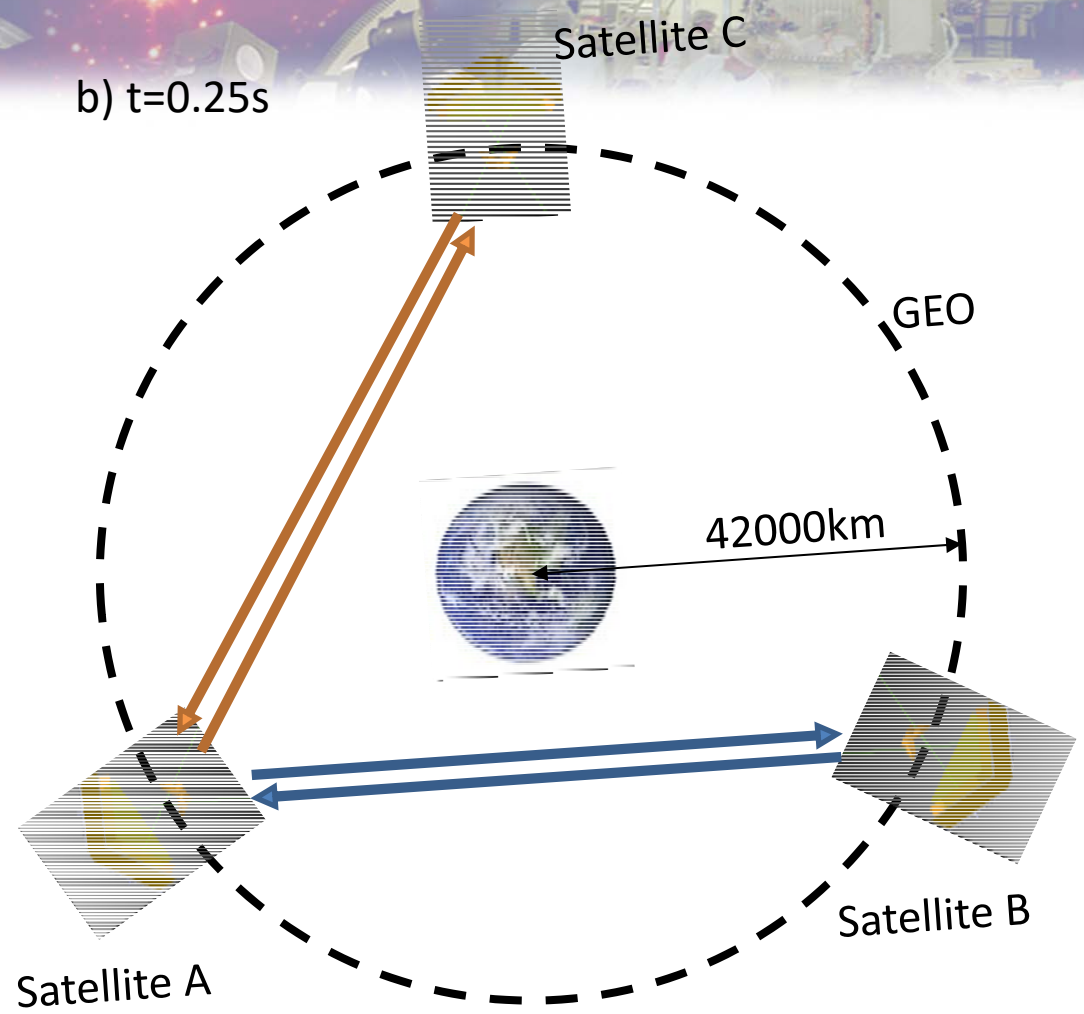


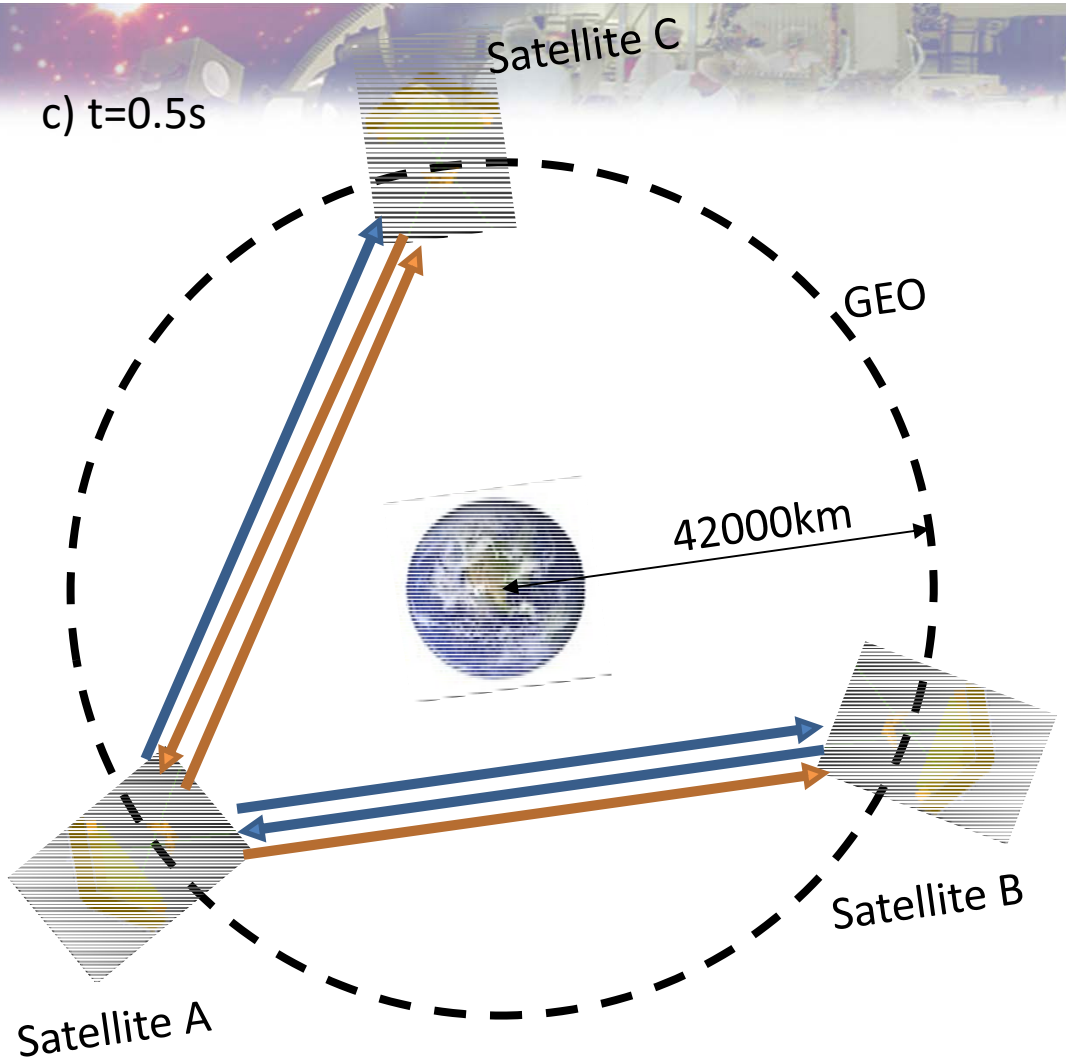





Spacecraft C
Spacecraft B
1e-8
1e-8
99.99%
0.01%
99.99%
0.01%
Phase Modulator f1
Phase Modulator f2
99%
99%
50%
50%
1%
1%
ψ_{12}
ψ_{12}
D2
D1
D3
Laser
φ_{12}
φ_{11}
φ_{13}
Spacecraft A

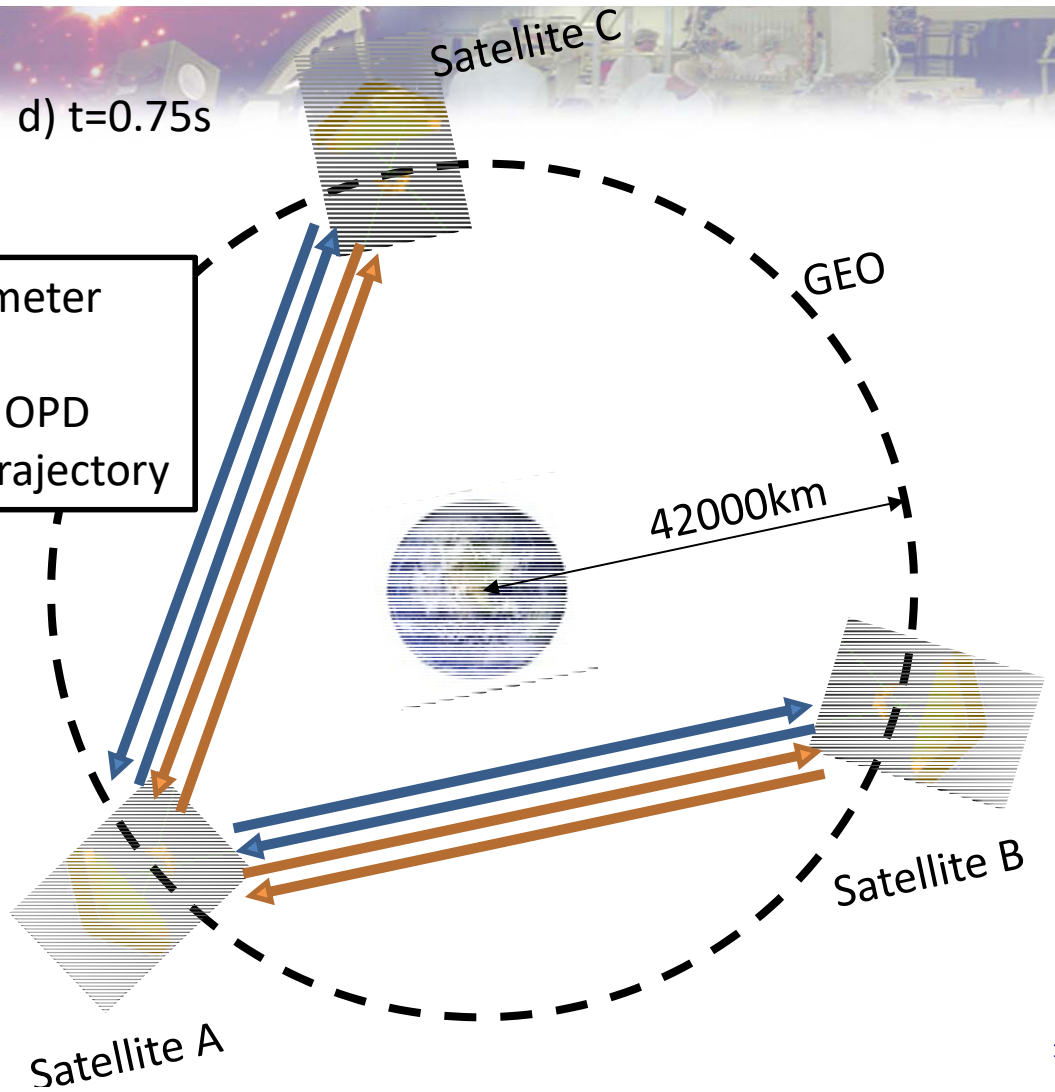

a) t=0s
Satellite C
GEO
72 000 km => 0.25s
42000km
72 000 km => 0.25s
Satellite A
Satellite B


b) t=0.25s
Satellite C
GEO
42000km
Satellite A
Satellite B

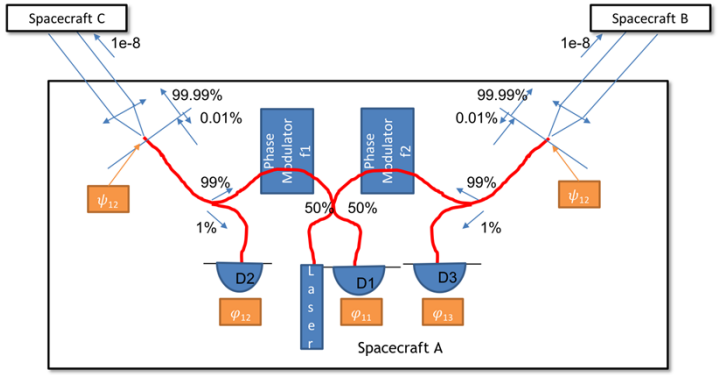

c) t=0.5s
Satellite C
GEO
42000km
Satellite B
Satellite A

d) t=0.75s

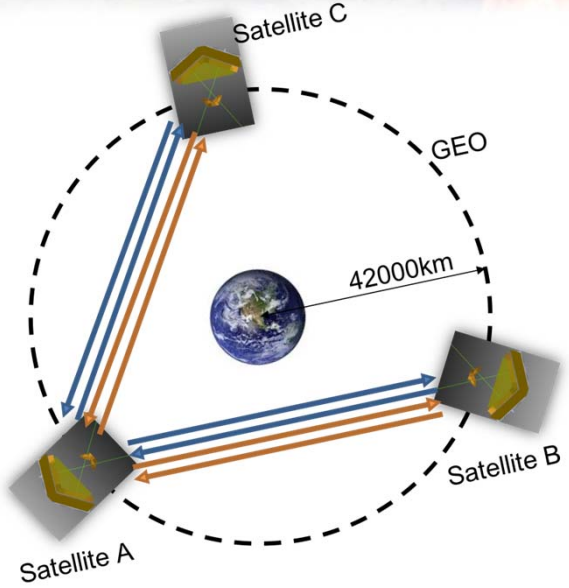
220 000 km interferometer
1 s light travel time
Measurement at zero OPD
Satellites on ballistic trajectory



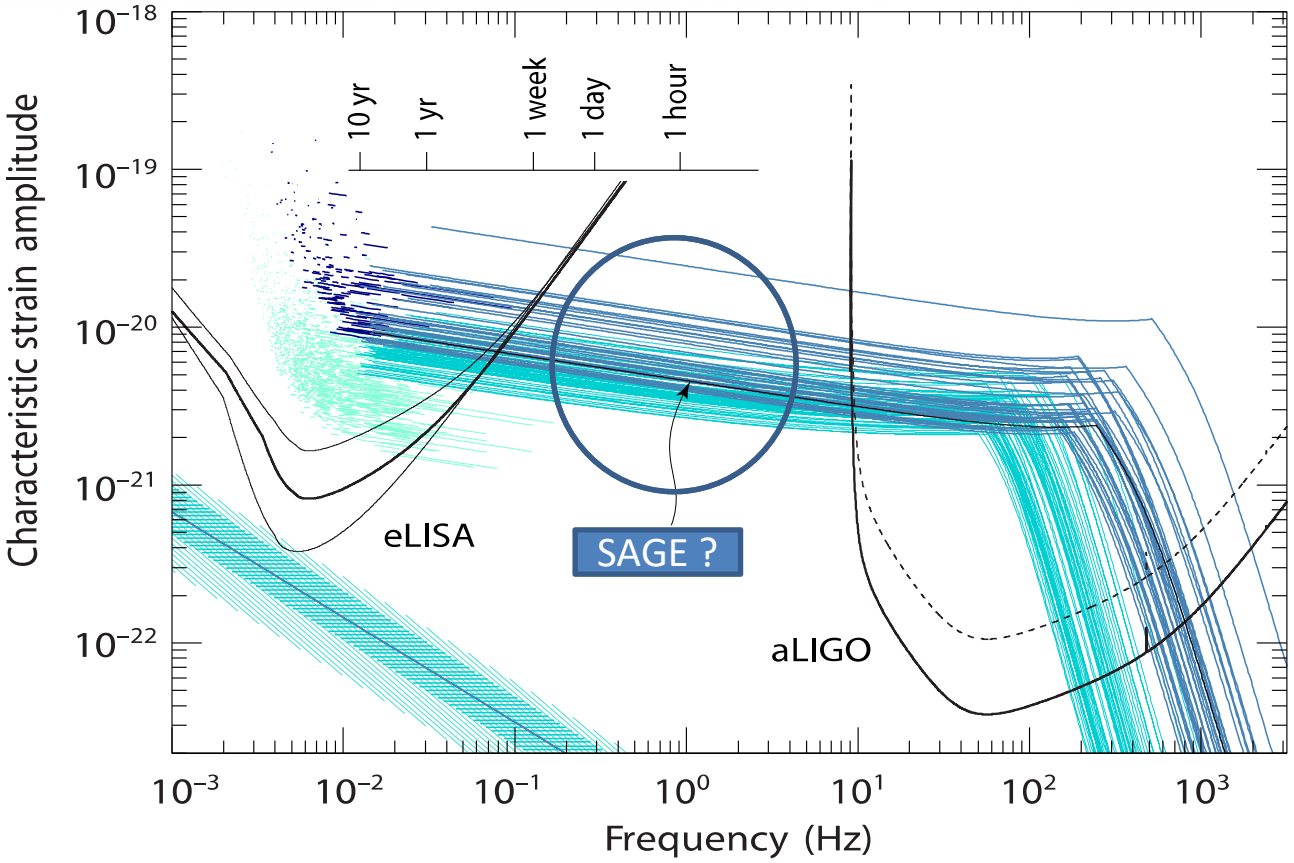
TDI



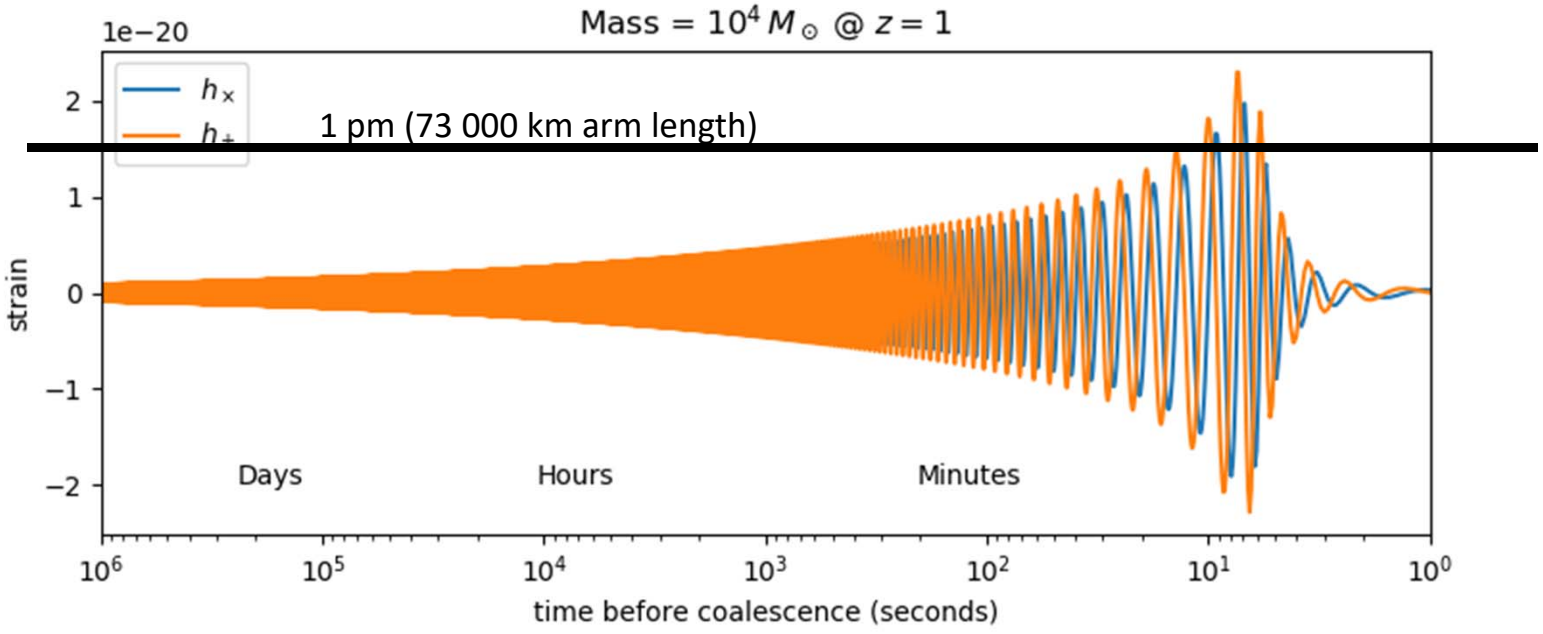
$$
\begin{aligned}
\varphi_{12}(t) &= {}_{21}(t+\Delta_{21}) - {}_{12}(t) + L_{21}(t)\\
\varphi_{21}(t) &= {}_{12}(t+\Delta_{12}) - {}_{21}(t) + L_{12}(t)\\
\varphi_{11}(t) &= 1/2({}_{12}(t) - {}_{13}(t))\\
\varphi_{13}(t) &= {}_{31}(t+\Delta_{31}) - {}_{13}(t) + L_{21}(t)\\
\varphi_{31}(t) &= {}_{13}(t+\Delta_{13}) - {}_{31}(t) + L_{12}(t)
\end{aligned}
$$



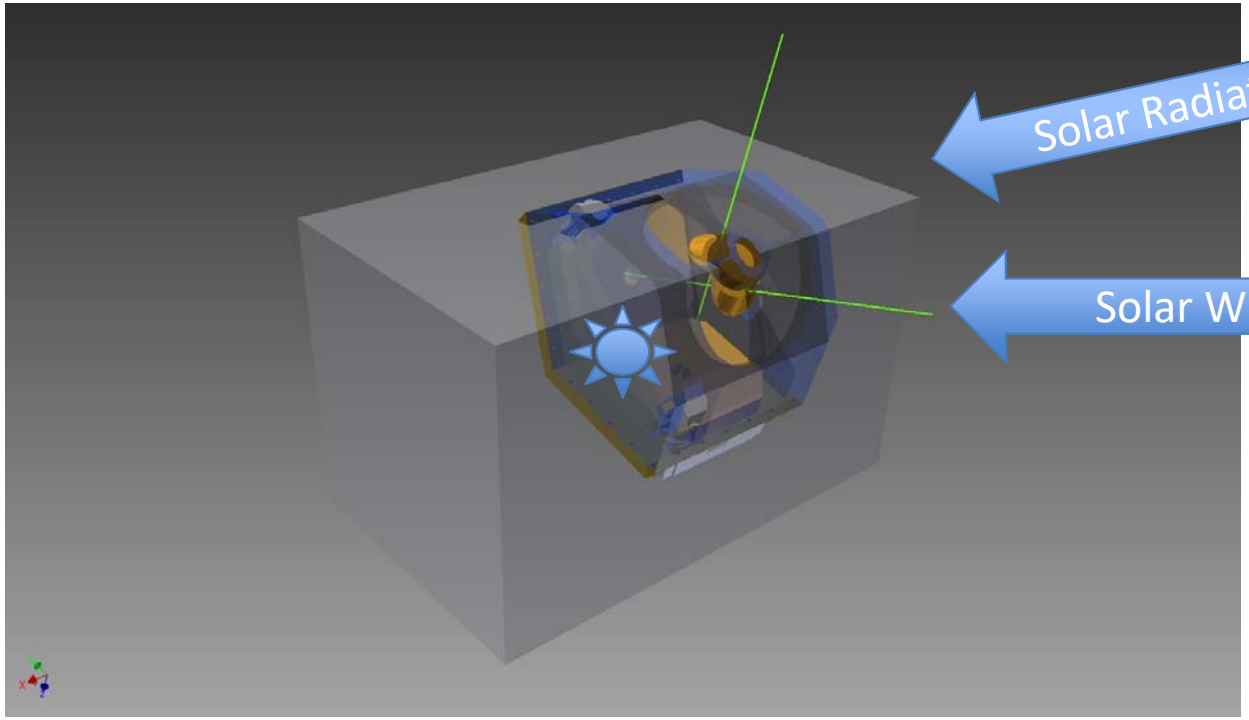
$$
\begin{aligned}
h(t) = {} & \varphi_{12}(t) + \varphi_{21}(t-\Delta_{12}) + 2\varphi_{11}(t-\Delta_{12}-\Delta_{21})\\
& + \varphi_{13}(t-\Delta_{12}-\Delta_{21}) + \varphi_{31}(t-\Delta_{31}-\Delta_{12}-\Delta_{21})\\
& - \varphi_{13}(t) - \varphi_{31}(t-\Delta_{13}) - \varphi_{11}(t-\Delta_{13}-\Delta_{31})\\
& - \varphi_{12}(t-\Delta_{13}-\Delta_{31}) - \varphi_{21}(t-\Delta_{21}-\Delta_{13}-\Delta_{31})\\
& + 2\varphi_{11}(t) - 2\varphi_{11}(t-\Delta_{21}-\Delta_{12}-\Delta_{13}-\Delta_{31})\\
h(t) = {} & L_{12}(t) + L_{21}(t-\Delta_{12}) + L_{13}(t-\Delta_{12}-\Delta_{21}) + L_{31}(t-\Delta_{12}-\Delta_{21}-\Delta_{13}))\\
& - L_{13}(t) - L_{31}(t-\Delta_{13}) - L_{21}(t-\Delta_{13}-\Delta_{31}) - L_{12}(t-\Delta_{13}-\Delta_{31}-\Delta_{12})
\end{aligned}
$$



Graph From ESA Gravitation Observatory Advisory team, final report 2016


Mass = $10^4 M_\odot$ @ $z = 1$
1e−20
$h_\times$
h_+
1 pm (73 000 km arm length)
strain
Days
Hours
Minutes
time before coalescence (seconds)

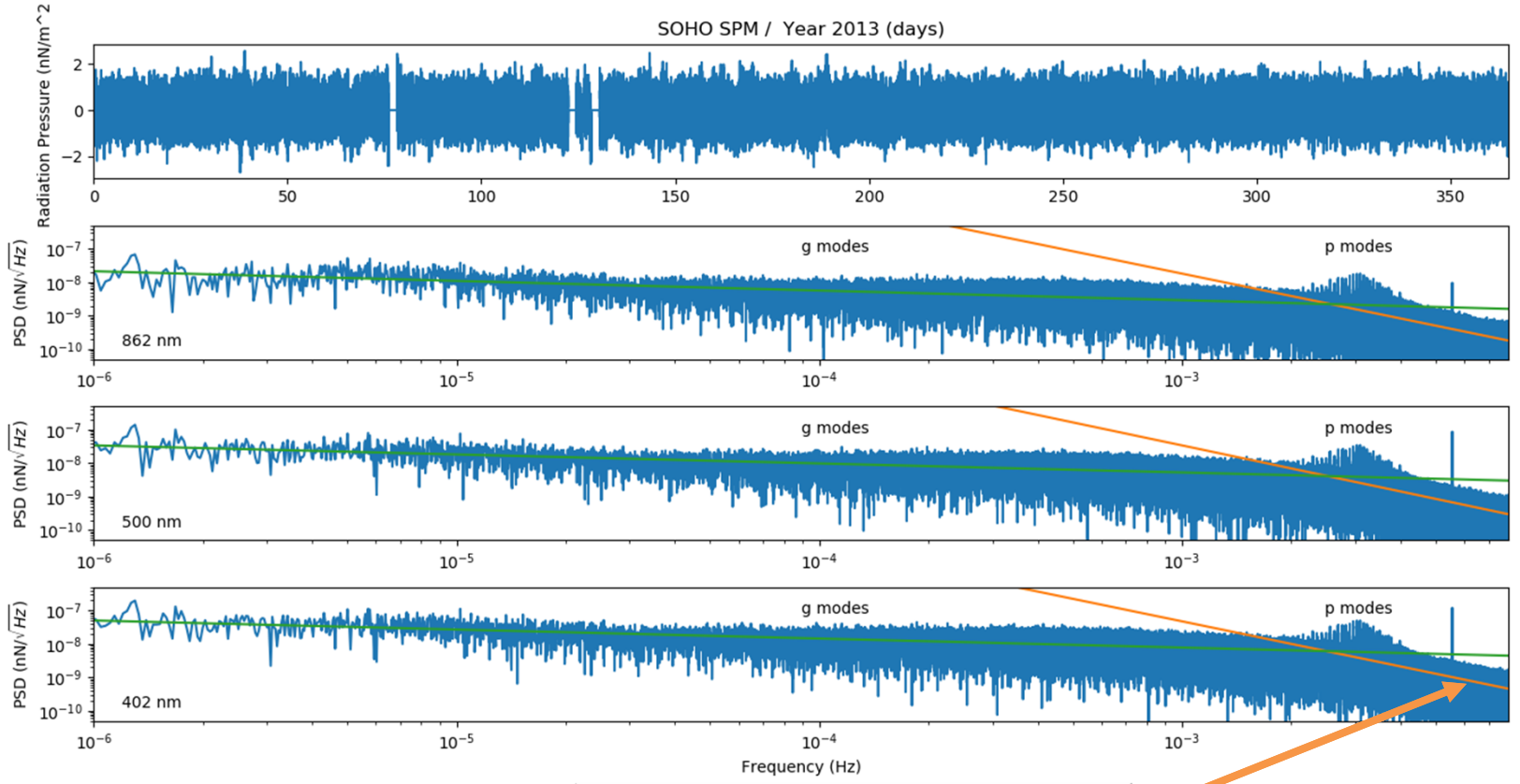
Sensitivity of SAGE



9 µN/m^2

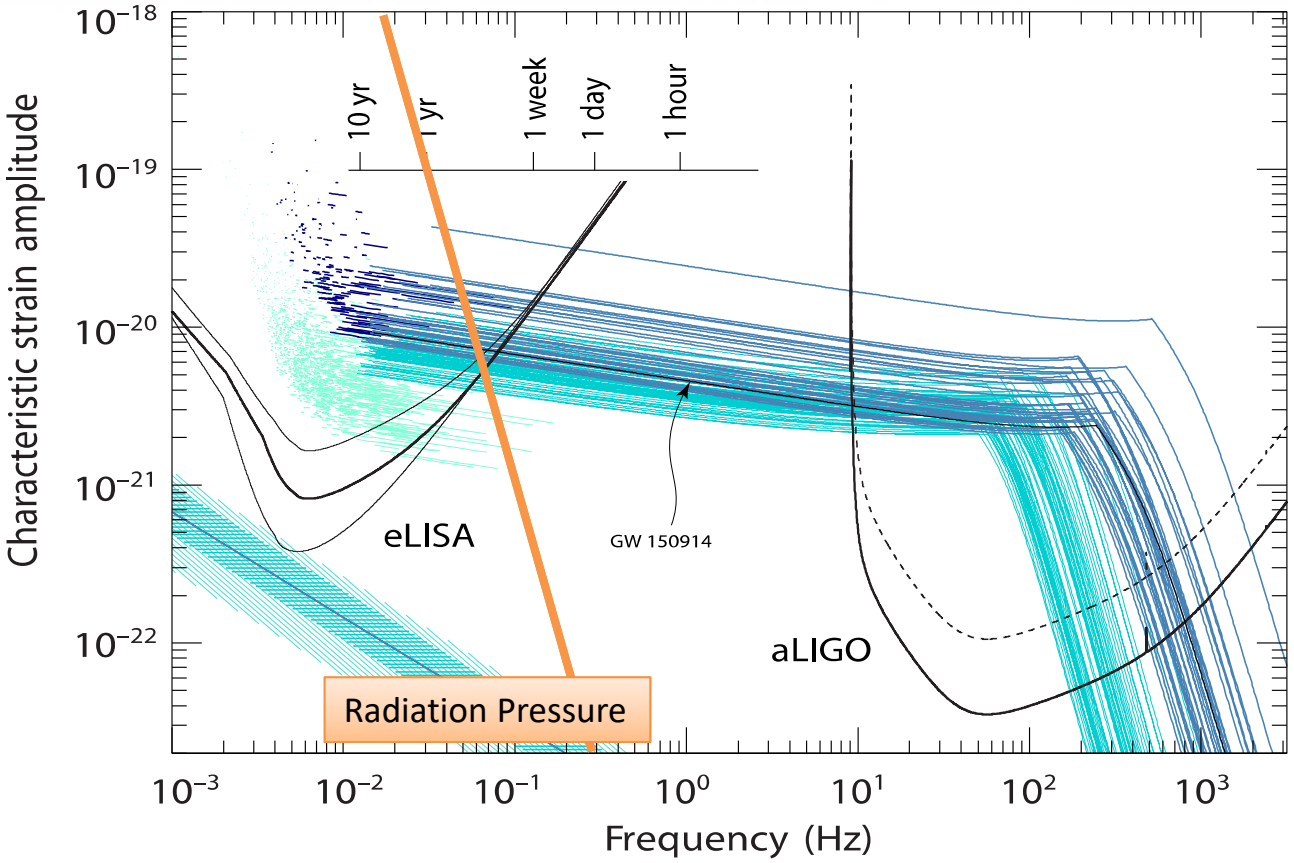
1-6 µN/m^2

Sensitivity of SAGE

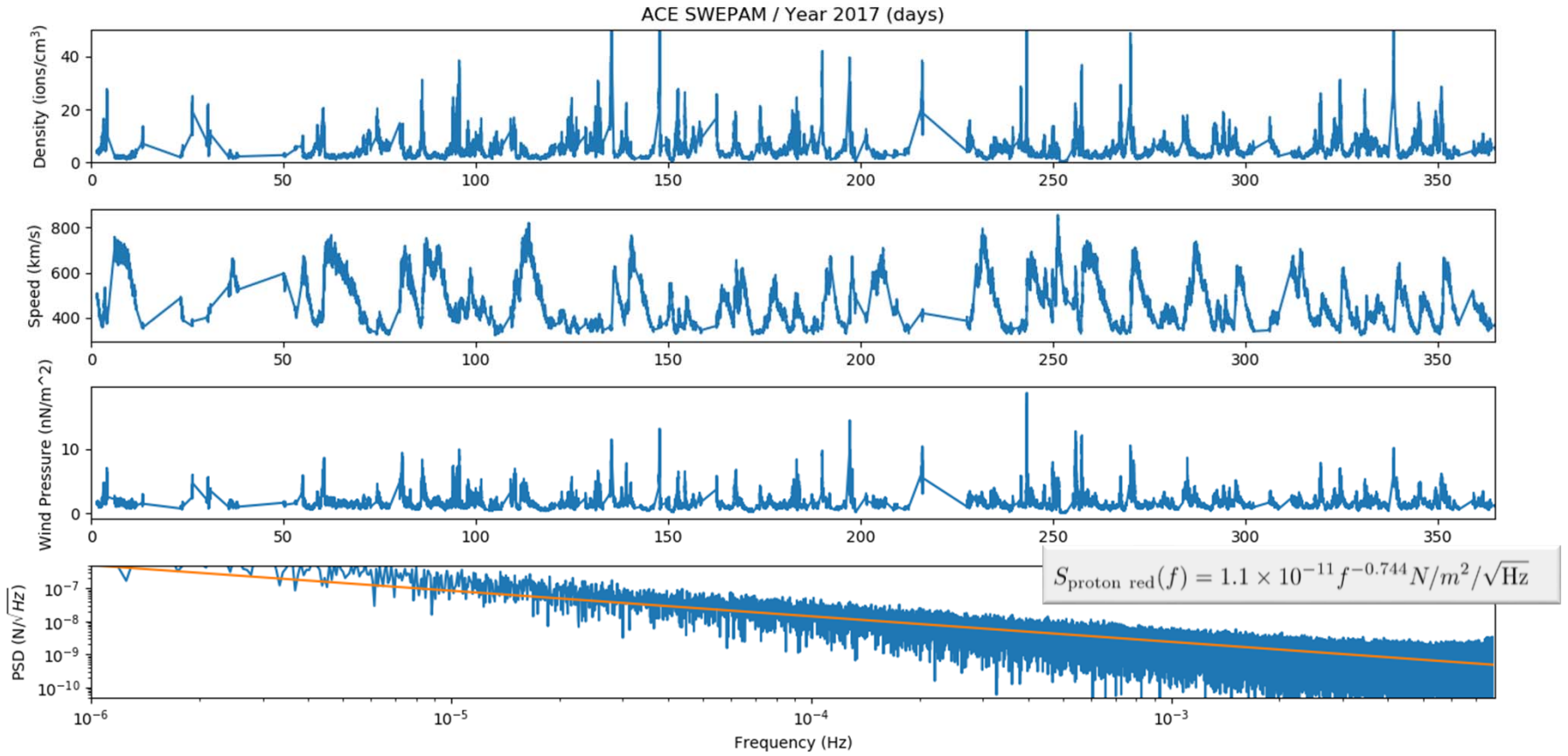


$$S_{\text{photon red}}(f) = 4.8 \times 10^{-15} f^{-2.25} N/m^2/\sqrt{\text{Hz}}$$

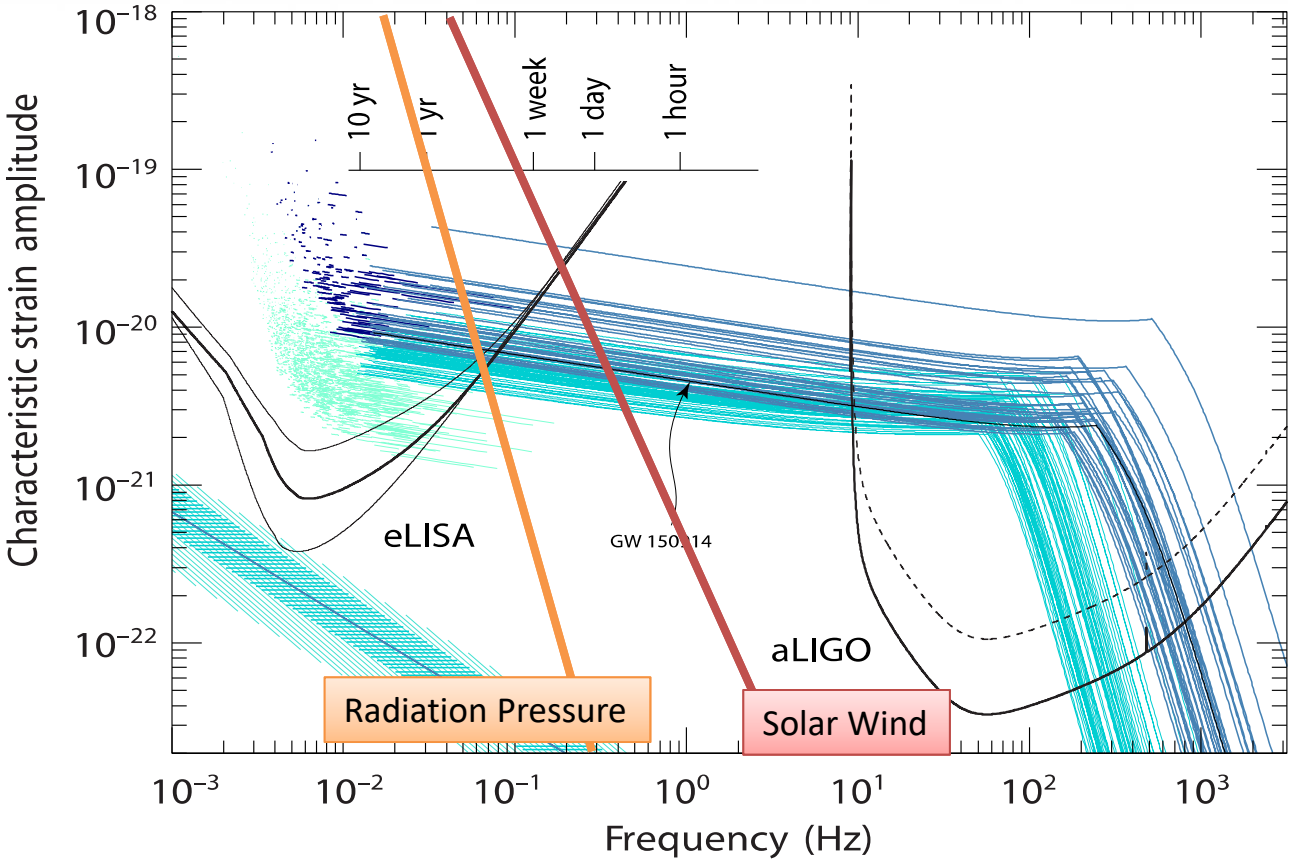
Sensitivity of SAGE



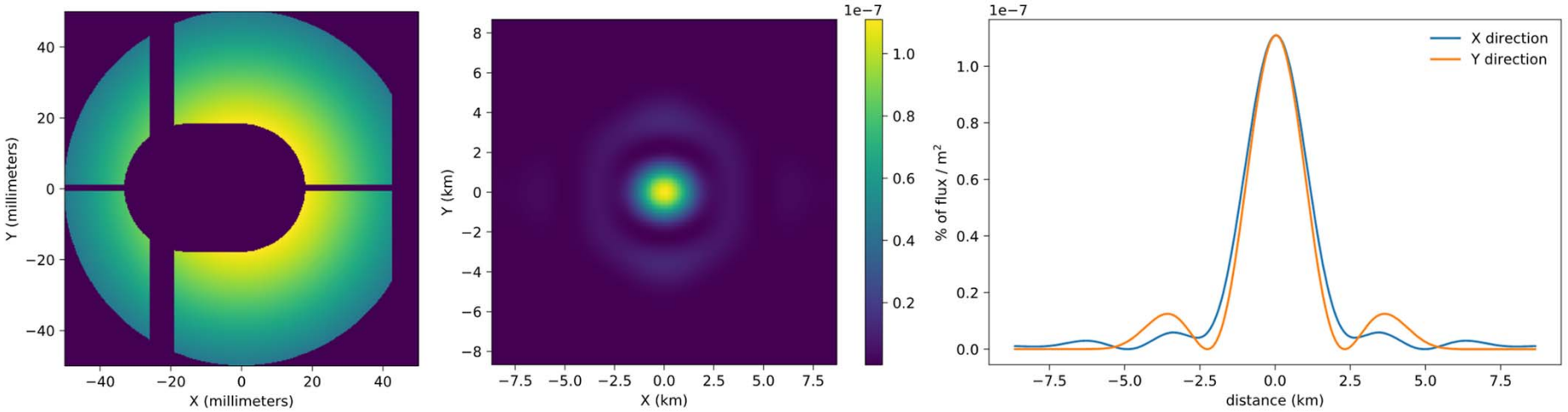
Sensitivity of SAGE



Sensitivity of SAGE



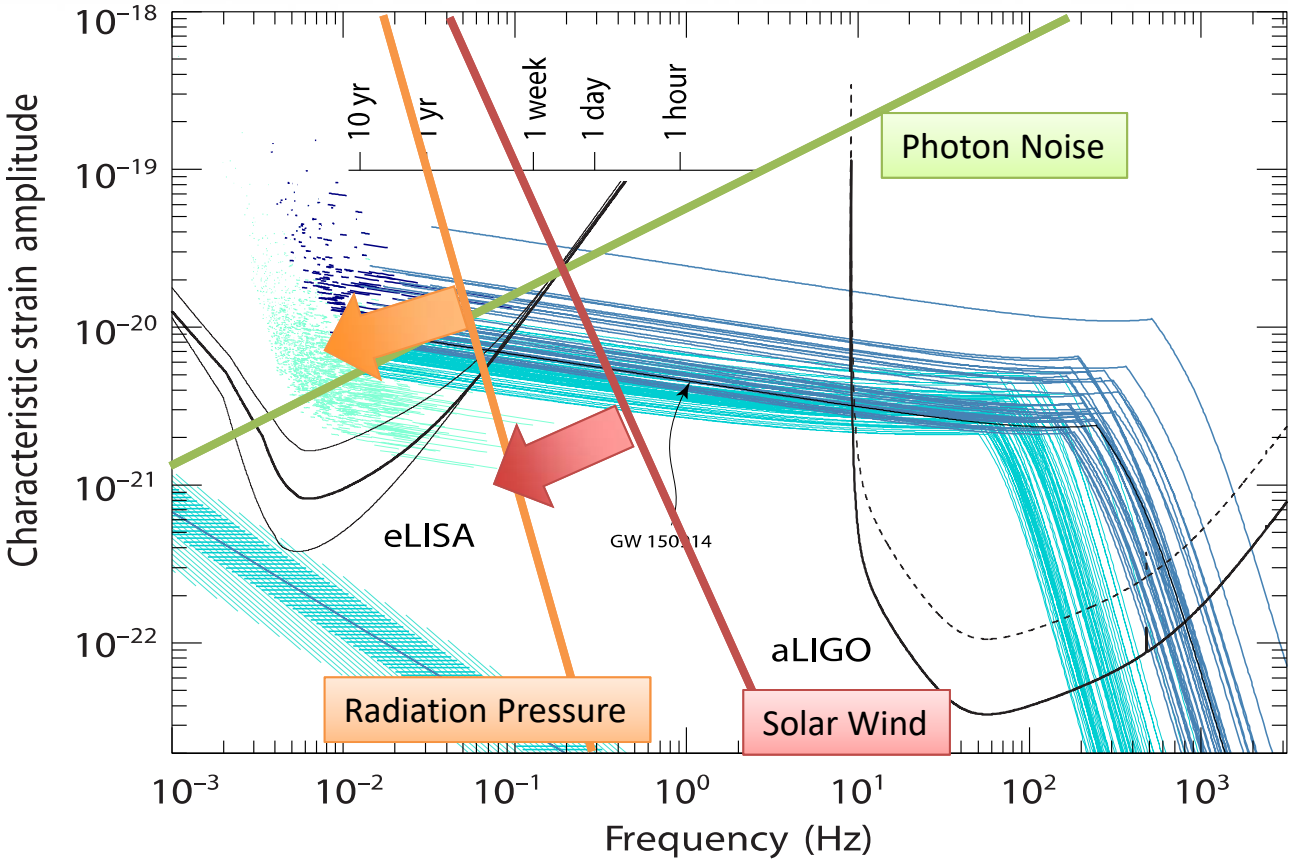
Diffraction analysis



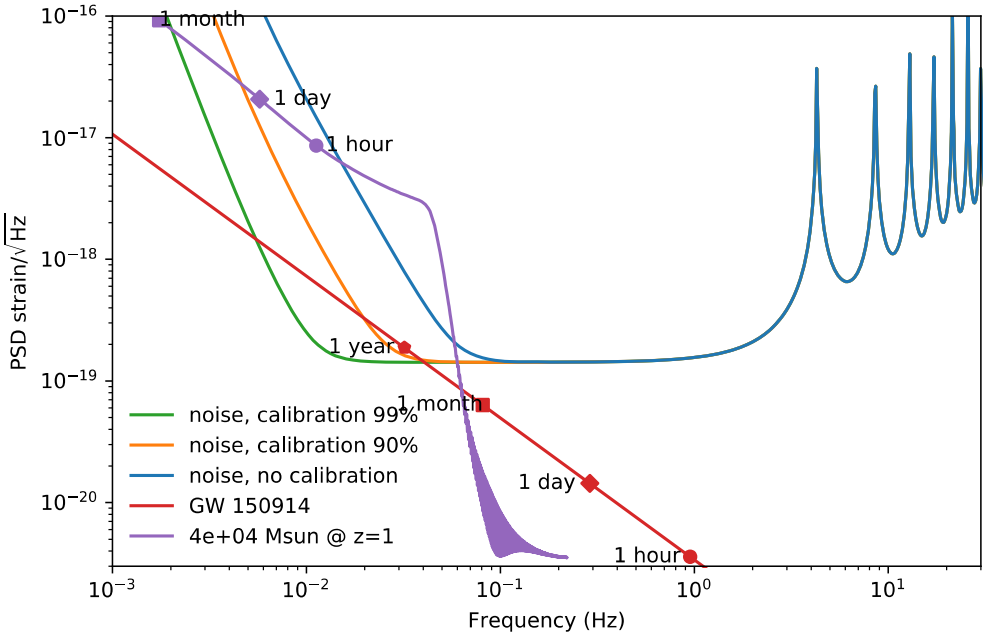
- Diffraction + fiber injection coupling cause an energy loss of 1.5 10^{-10} between the two satellites: 100mW=>15pW

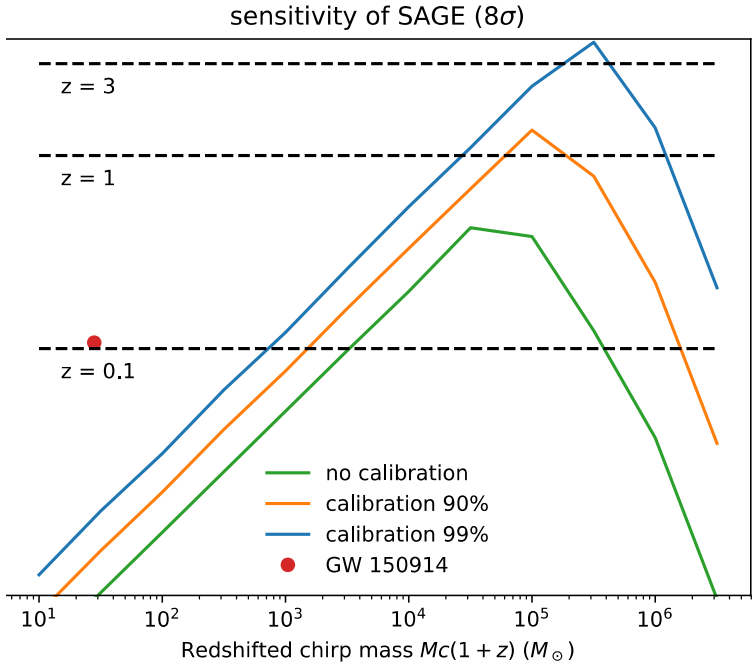
$$s\frac{}{\frac{hc\lambda}{2\square P_{photons}}} = 23\,pm/\sqrt{Hz}$$

Sensitivity of SAGE



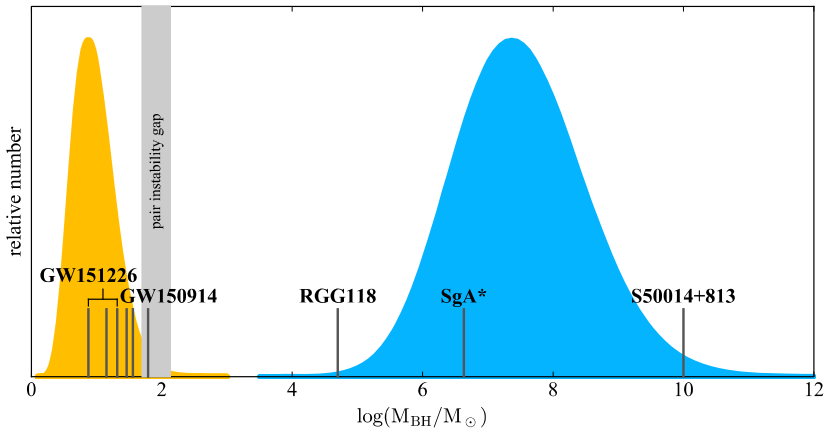
Sensitivity of SAGE



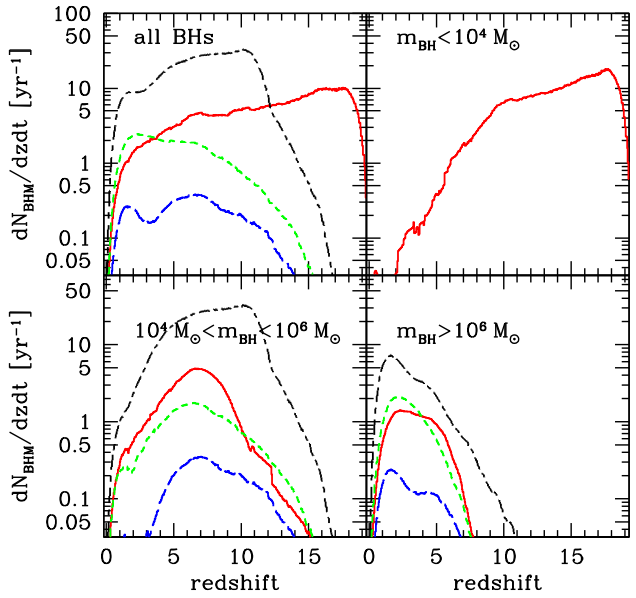


But…

- No 10^4 IMBH?



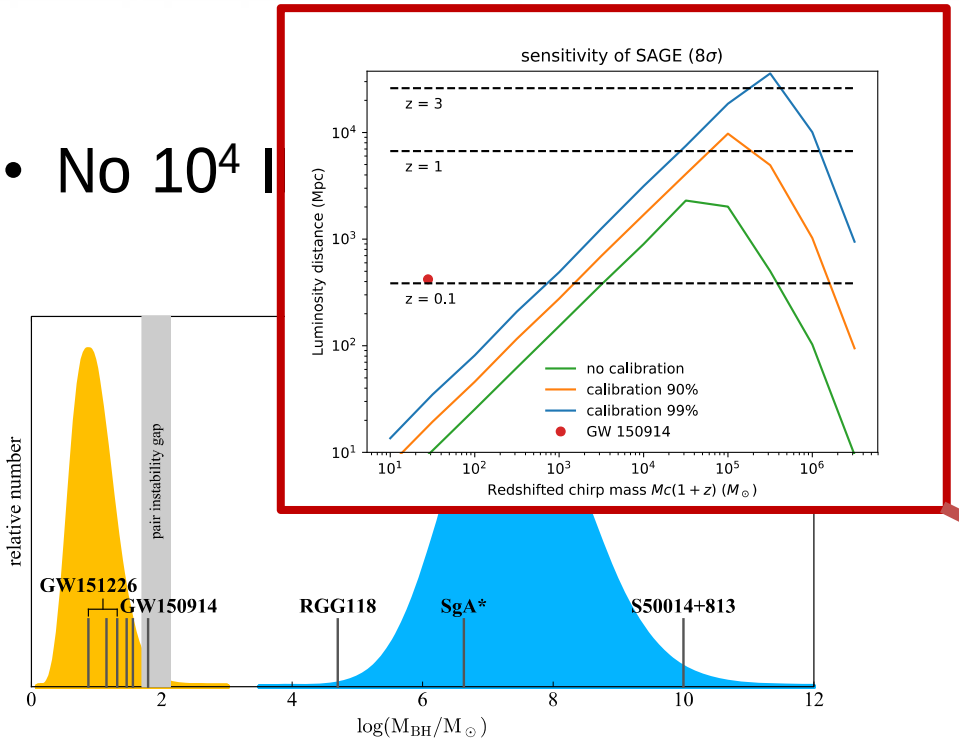
M. Colpi, A. Sesana, 2018



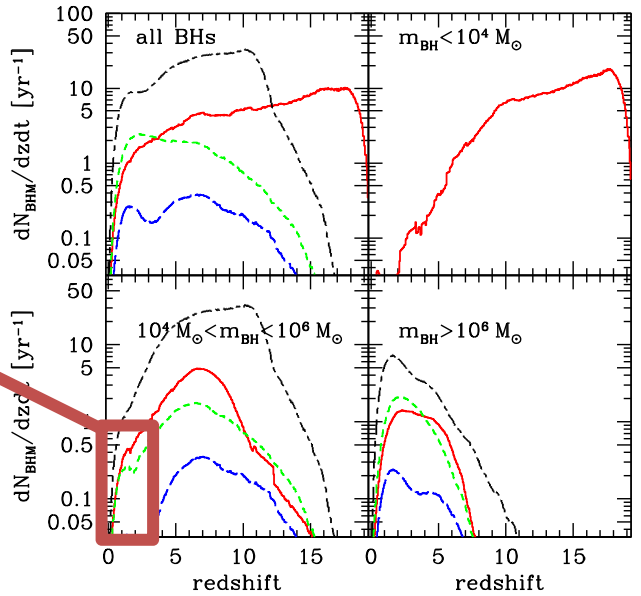
A. Sesana, M. Volonteri, and F. Haardt, 2007

But…

- No 10^4 I



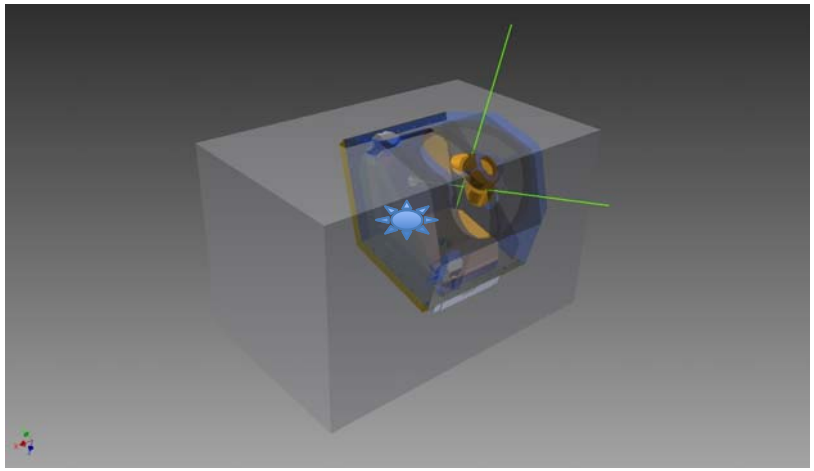
M. Colpi, A. Sesana, 2018



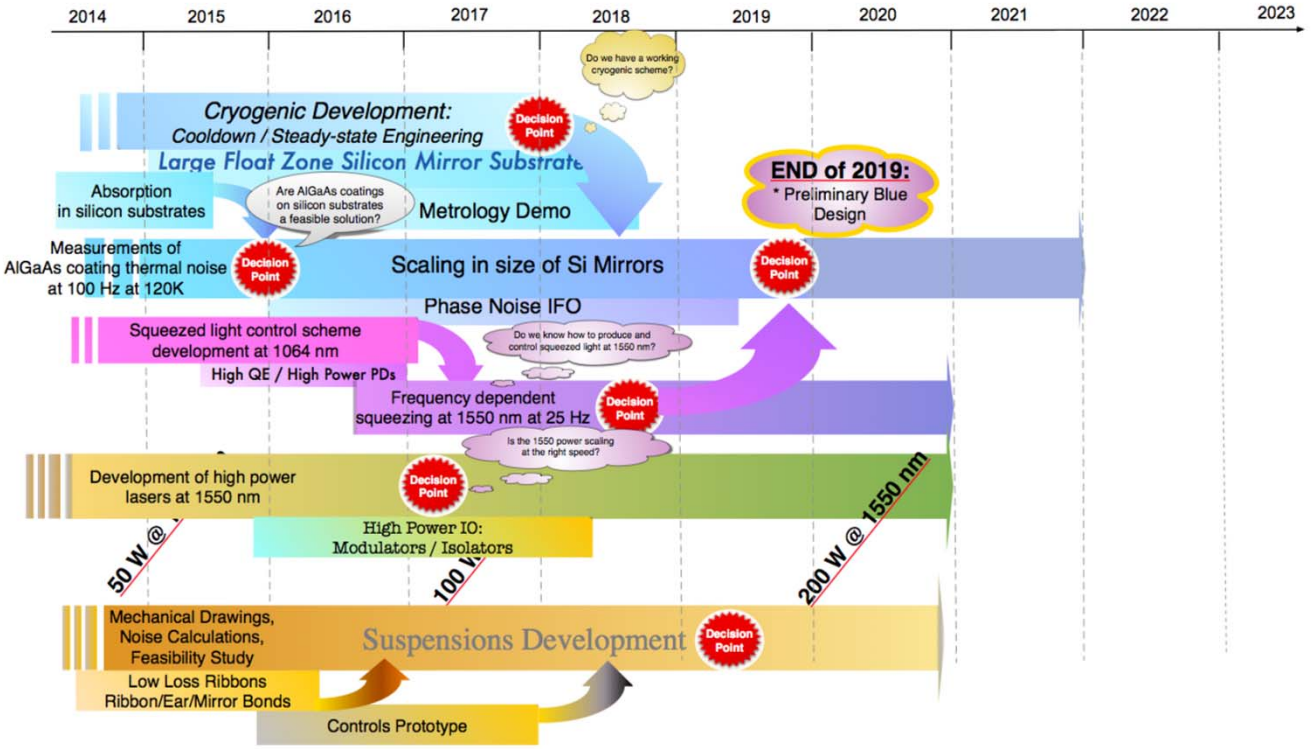
A. Sesana, M. Volonteri, and F. Haardt, 2007

But…

- Technical challenges:
  - Orbitography
  - Thermal expansion (20pm/sqrt(Hz)



To conclude



LIGO timeline