Gravitational wave **L**aser **IN**terferometry **T**riangle

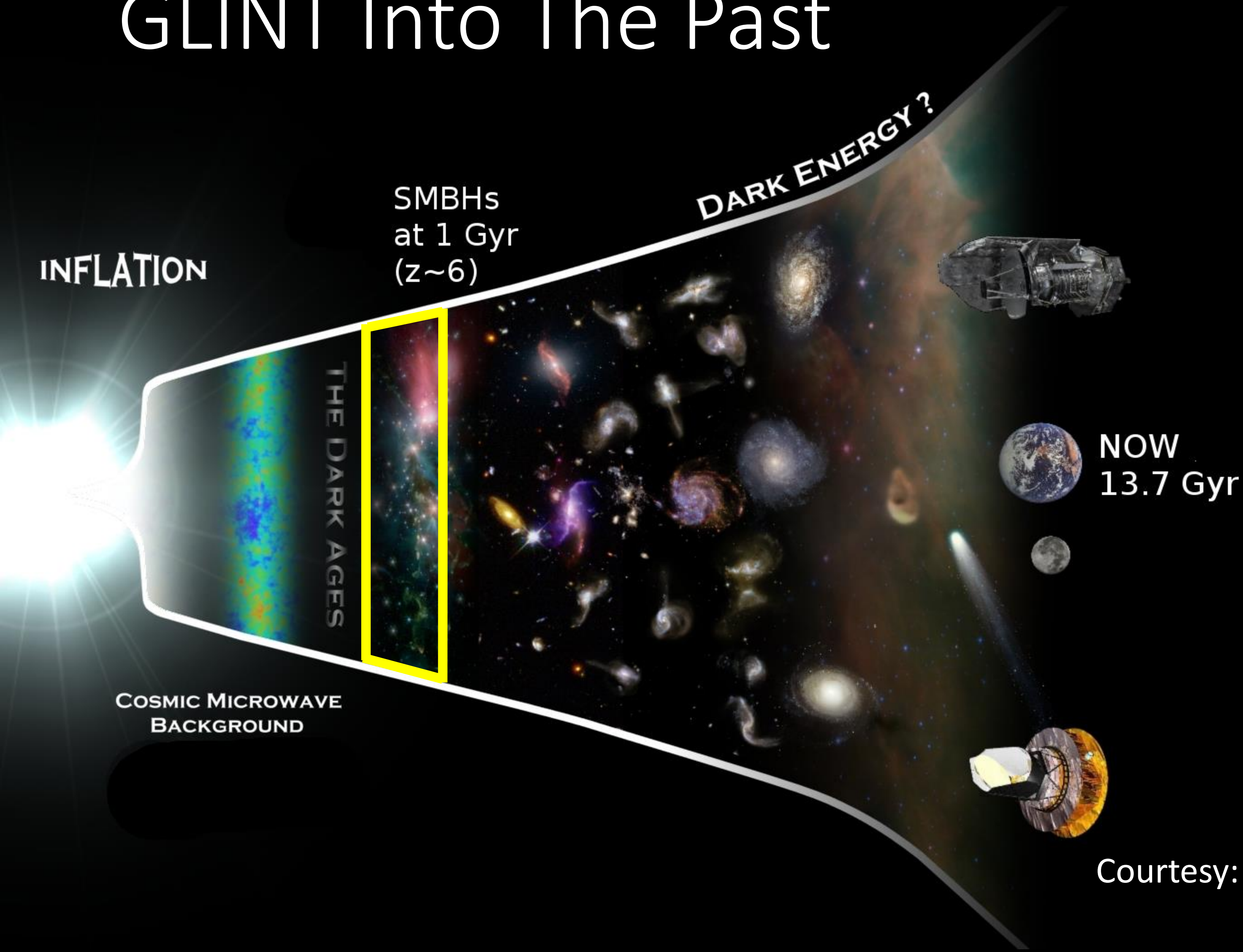
Summer School Alpbach 2015

Team Red

GLINT

Exploring the early Universe with gravitational waves

GLINT Into The Past



Courtesy: Planck Mission

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  - Configuration
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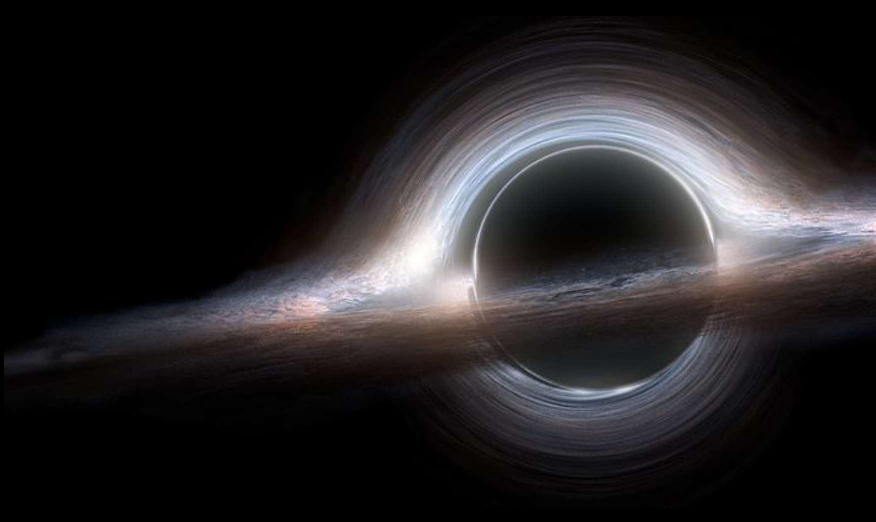
  - Budgets
  - Structural Design

Courtesy: NASA

Science Case

Exploring Einstein’s Theory of General Relativity with **Black Holes**

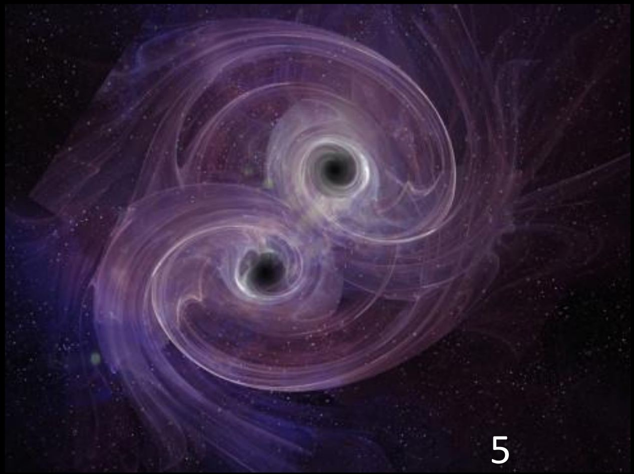
- When did the first black holes of several solar masses appear?
- How were they formed?
- What were their properties?
- How did they evolve?



Science Case – Additional

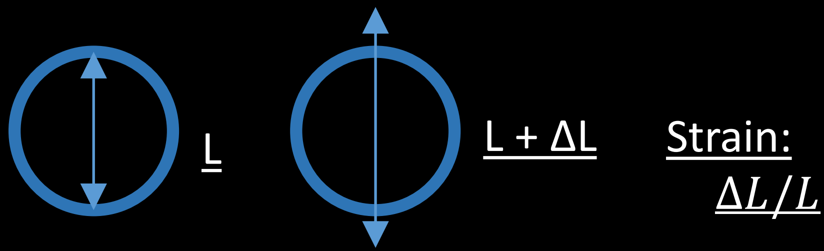
Exploring **Einstein’s Theory of General Relativity** with **Massive Binary System**

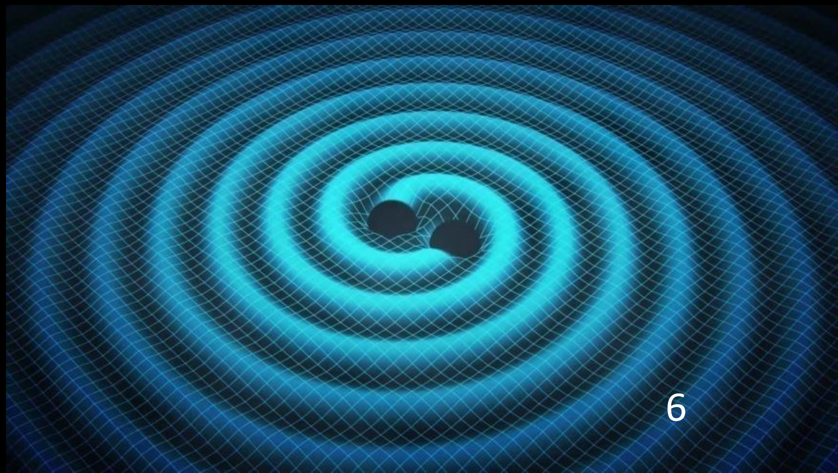
- How fast did the Universe expand and what are the dark matter and dark energy densities?
- Is the theory of general relativity the best description of gravitation?
- How did binary systems merge?



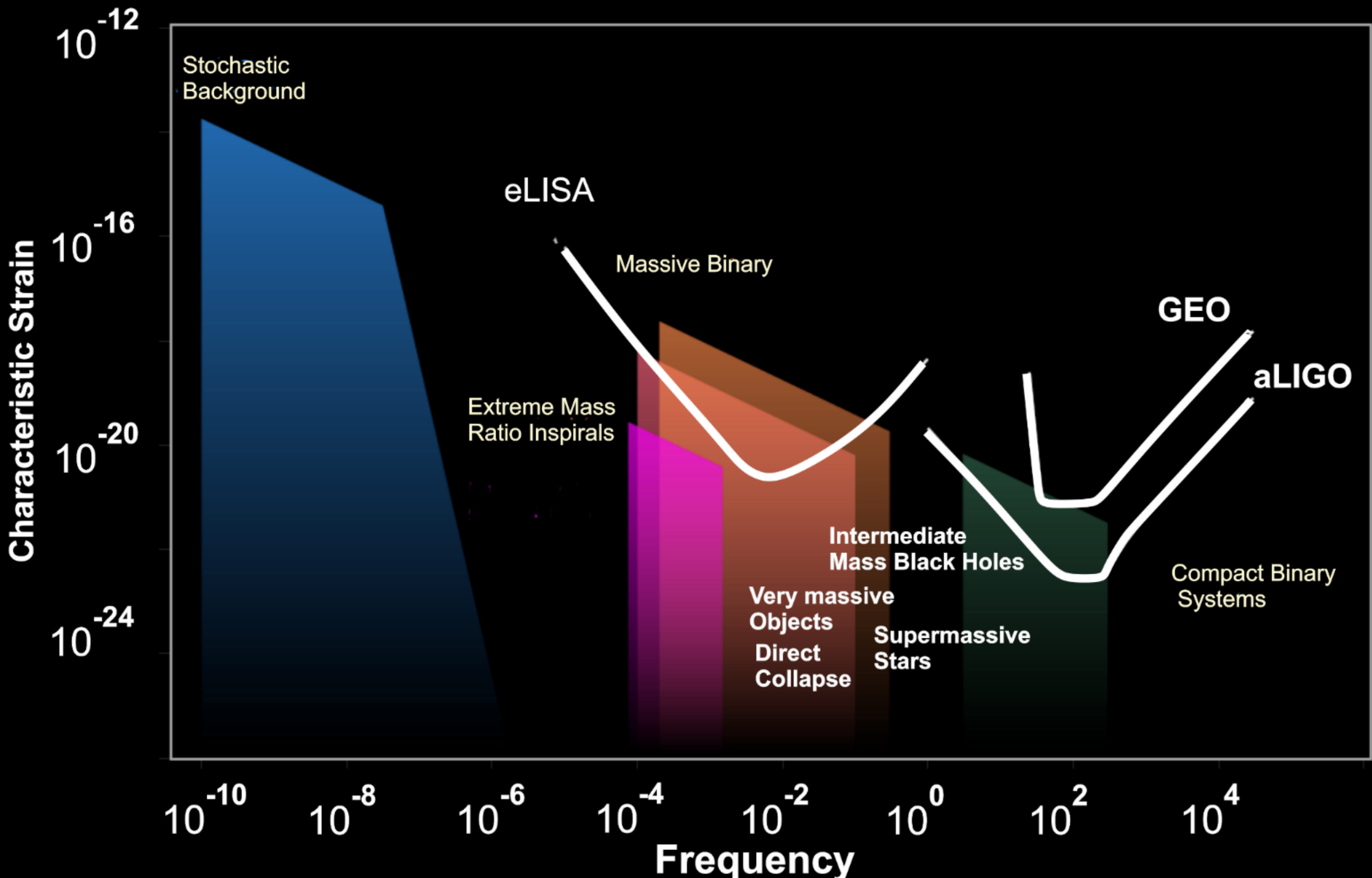
Gravitational Waves

- Acceleration of a massive object causes ripples in spacetime
- The ripples propagate as waves and are characterized by **frequency, strain** (amplitude) and **polarization**
- The passing gravitational wave changes the time light takes to travel a certain distance
- This change in distance can be measured





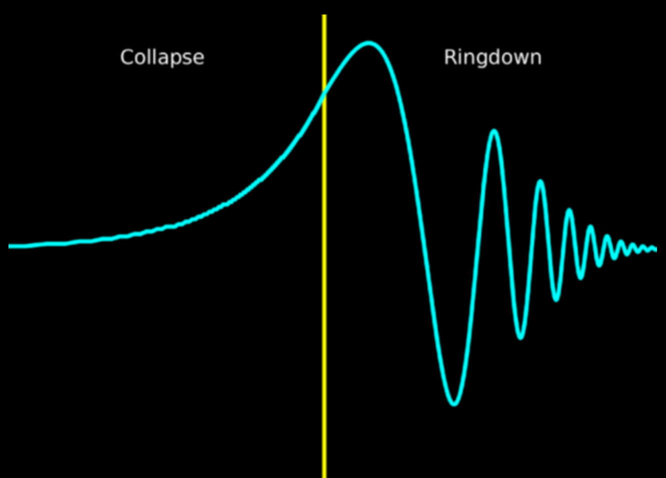
Sources and observatories



Waveforms

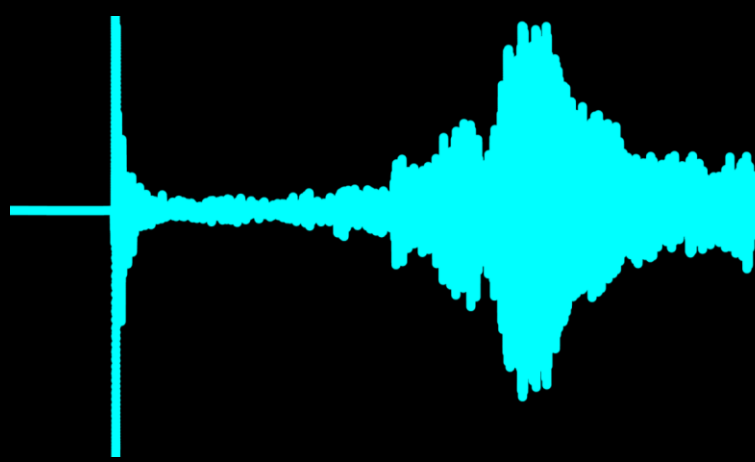
- The gravitational wave trace from formation of black holes
- Different events can be distinguished since they have different signature waveforms

Direct collapse of a hydrogen cloud



Duration: 10 s

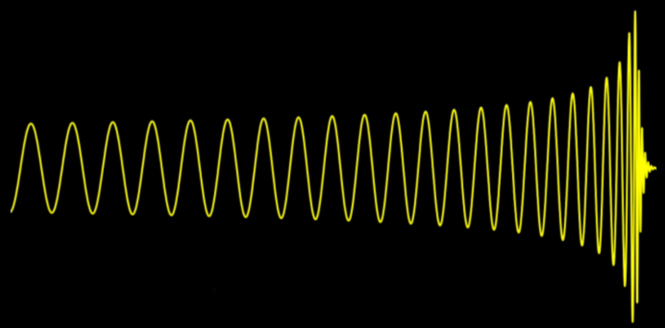
Supernova core collapse (300 Msun)

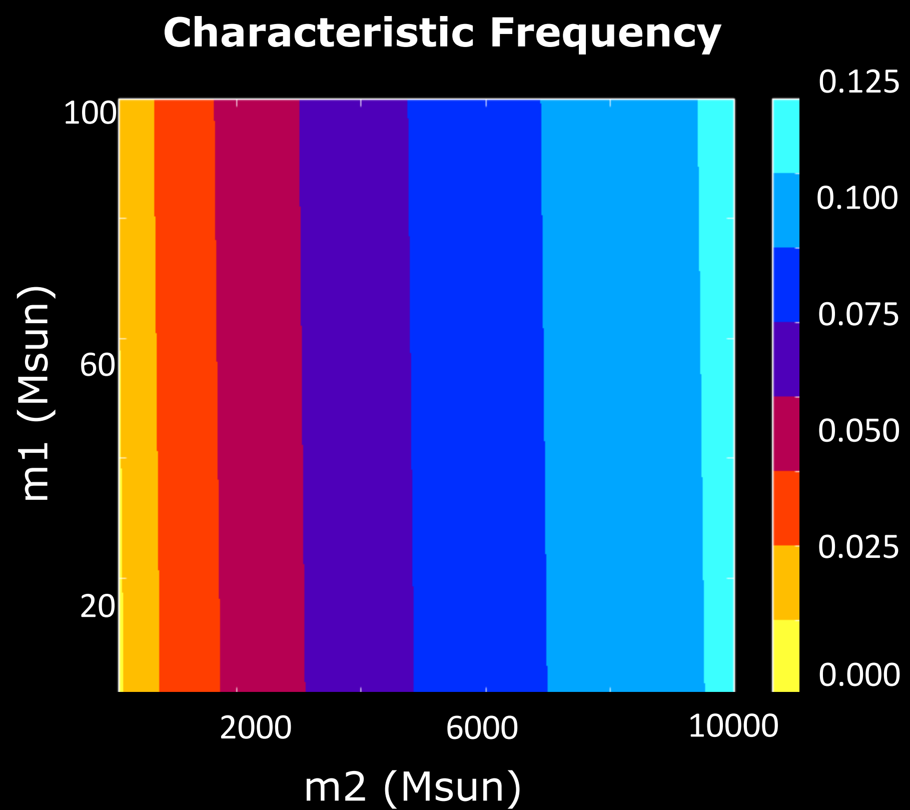


Duration: 20 s

Waveforms

Inspirals into IMBH





Duration: years

Primary Scientific Objectives

1. **Direct Collapse Black Holes (DCBH)** in the range of 10^4 - 10^6 solar masses.

2. **Collapse of Very Massive Objects (VMO)** in the range of 10^2 - 10^5 solar masses.

3. **Collapse of Supermassive Stars (SMS)** in the range of 260-800 solar masses.

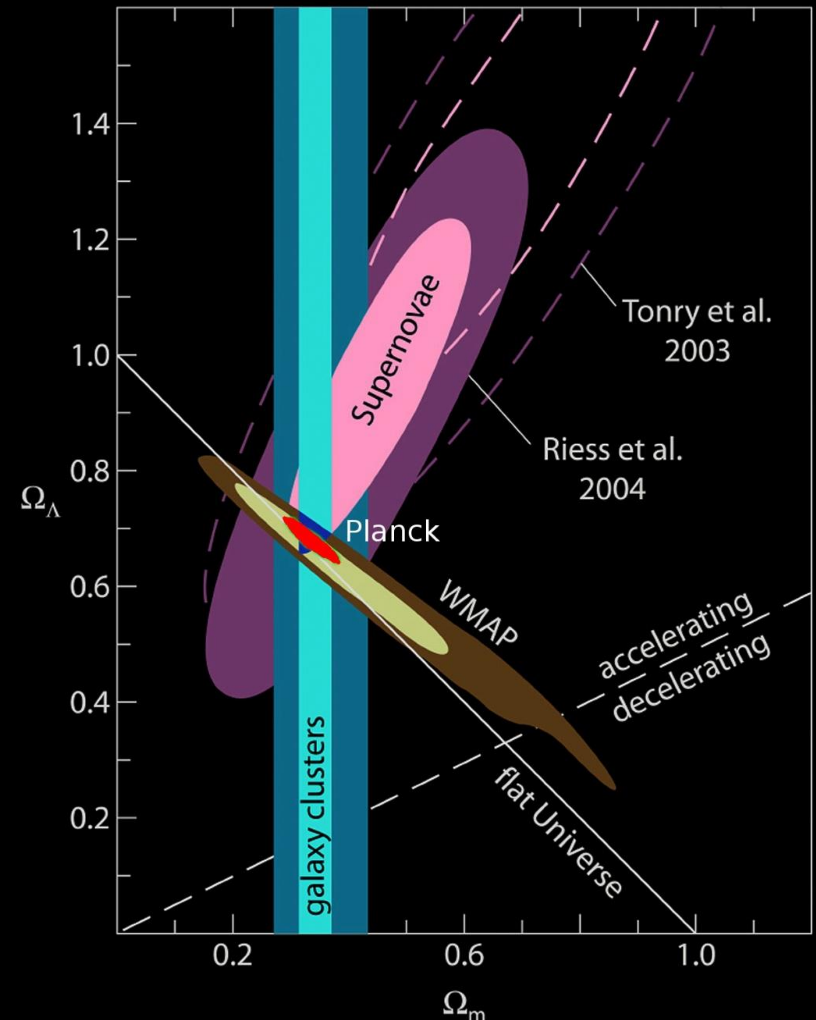
4. Two **Merging Black Holes** in the range of 10^2 - 10^5 solar masses.

5. **Inspiraling** of massive objects into a black hole in the range of 10^2-10^3 solar masses

Secondary Scientific Objectives

1. Massive **binary systems** ranging from a few to $\sim 10^4$ solar masses
2. Observation can be combined with (JWST, Athena) to obtain information about the early Universe

We can corroborate or improve on the current constraints for the **matter and dark energy densities** obtained from experiments like NASA's WMAP and ESA's Planck missions.



Science Requirements

- Sources of interest

Sources	Sensitivity (strain)	frequency (Hz)	collapse duration (s)	production rate / year
Supermassive Star	5×10^{-24}	0.4-1	5-60	10^{7}
Very Massive Object	10^{-23}	0.01-0.2	10-100	4000
Direct Collapse	10^{-23}	0.01-0.1	10-100	10^{4}

→ Observation time
t = 1 yrs

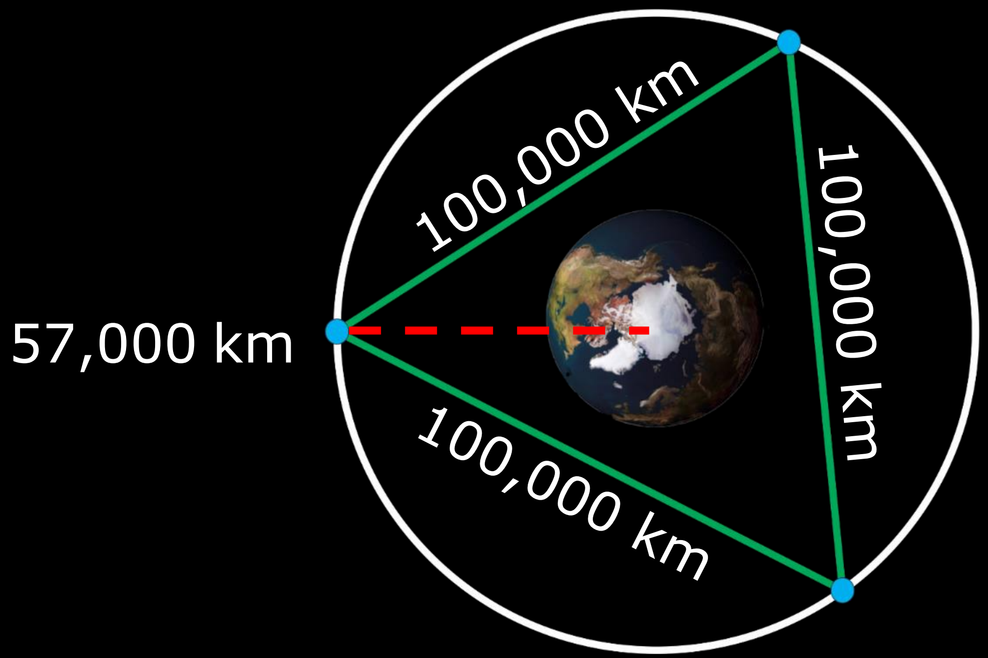
Options to measure grav. waves

- Laser Interferometry – changes in distance
  1. Michelson Interferometer
  2. Fabry-Pérot Interferometer

- Optical Lattice Clocks – changes in ticking rate
  Technology not sensitive enough

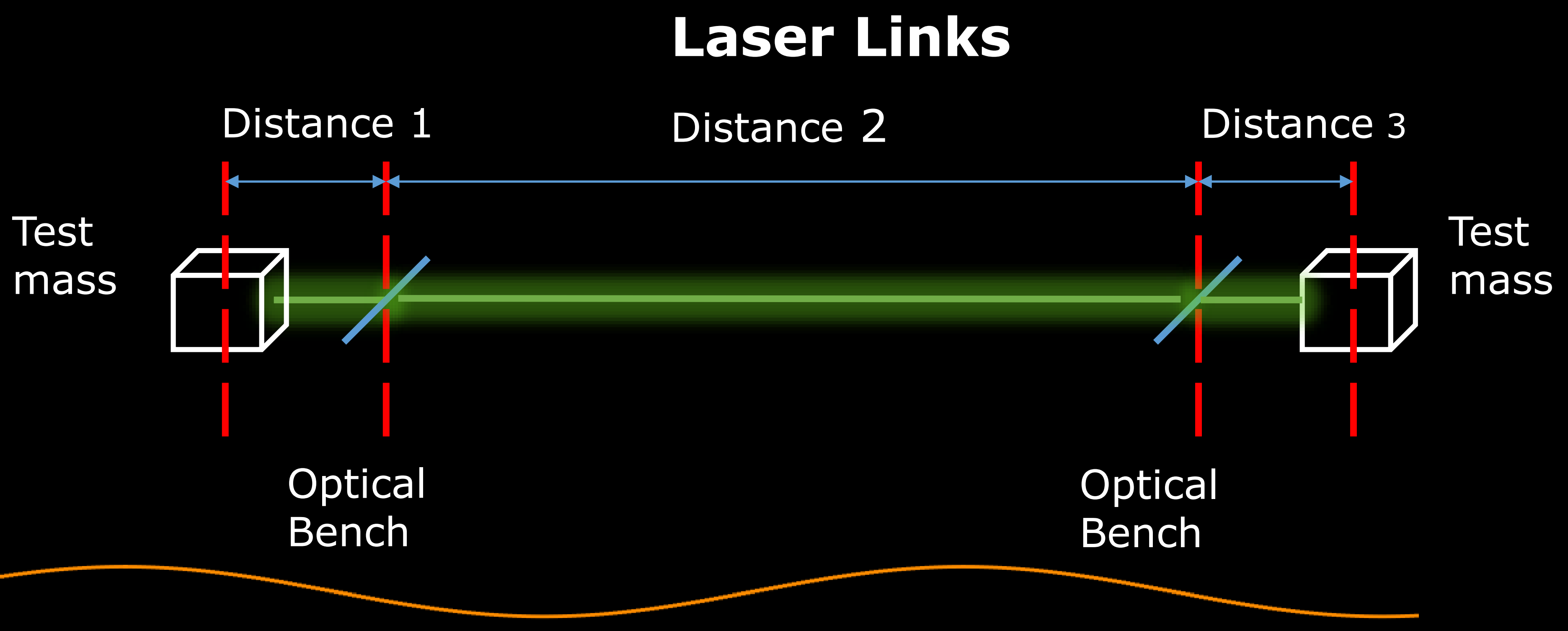
- Bose Einstein Condensates
  Only theoretical studies performed

Mission Profile Overview

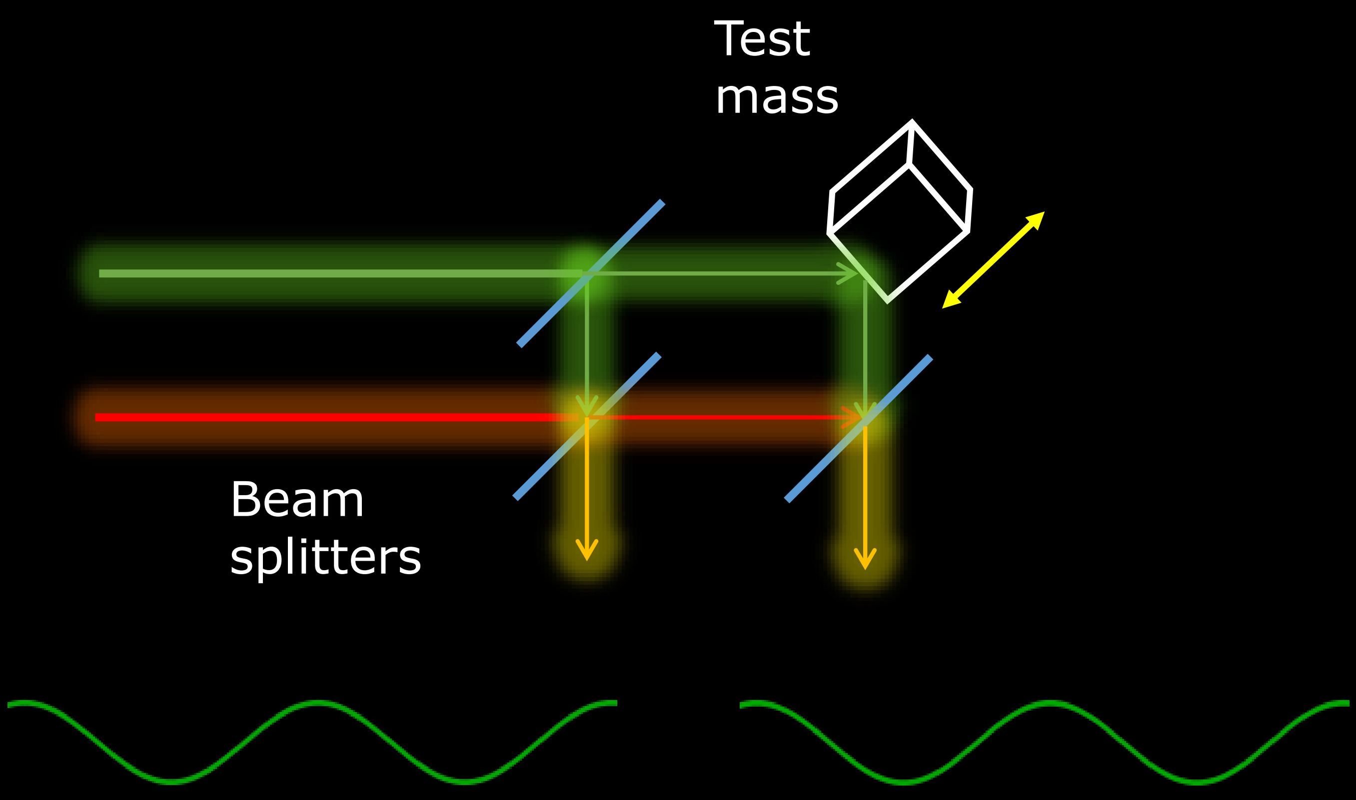


Not to scale

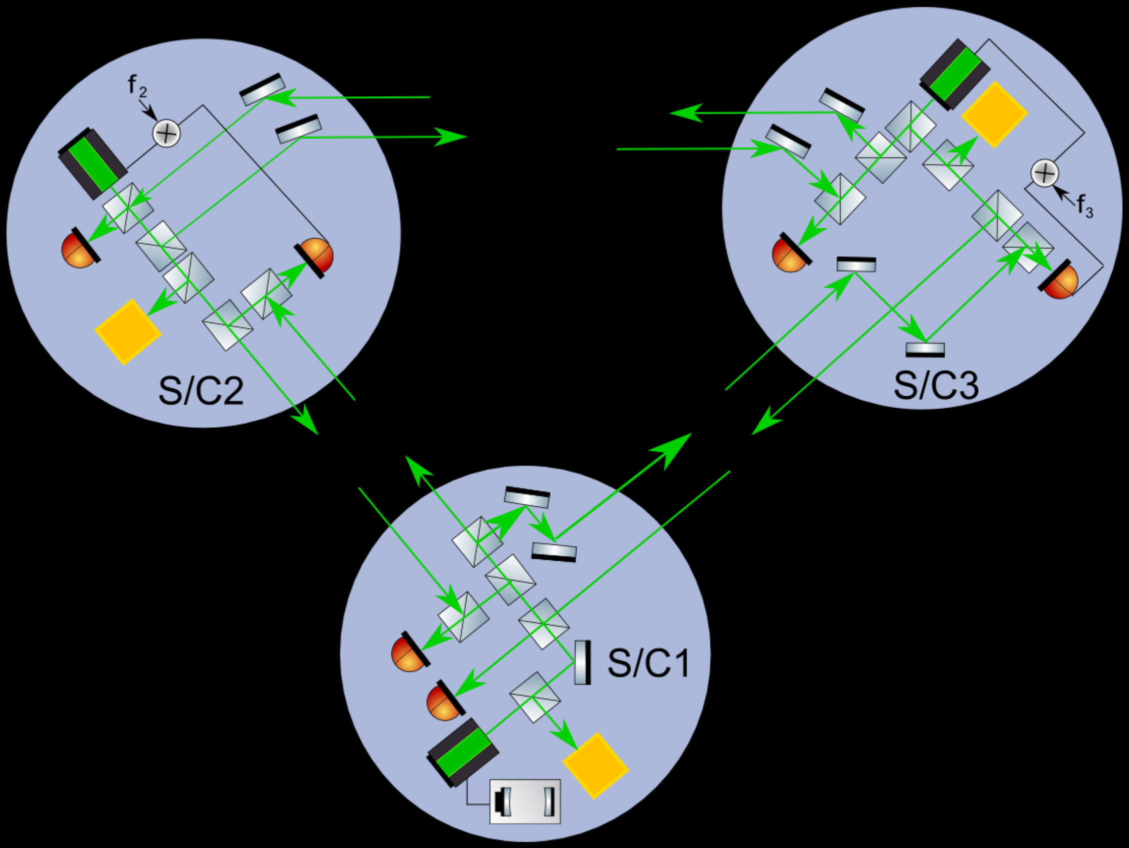
Working principle per arm



Heterodyne Interferometry



Optical Setup Overview



Measurement system requirements

Requirement $\delta h = 5 \cdot 10^{-24}\, 1/\sqrt{Hz}$ 0.01 Hz to 1 Hz

The main features of the measurement instrument are:

- Interferometric measurement system
- Drag-free system (free fall)

Interferometric measurement system

Requirement $\delta x = 10^{-16}\, m/\sqrt{Hz}$ 0.01 Hz to 1 Hz

1) **Transfer function**
2) **Shot noise**
3) **Relative intensity noise (RIN)**
4) **Frequency noise**
5) **Optical Pathlength**
6) **Phasemeter**

Describes how the gravitational waves couple to the antenna in the detection band

$$L_{arm} = 10^8\, m$$

Interferometric measurement system

Requirement $\delta x = 10^{-16}\, m/\sqrt{Hz}$ 0.01 Hz to 1 Hz

1) Transfer function

2) Shot noise

3) Relative intensity noise (RIN)

4) Frequency noise

5) Optical Pathlength

6) Phasemeter

Noise caused by fluctuations in detected photon count rate

Requirements:

P_{sent}=10W

D_{teles}=1.5m

P_{rec}= 0.017 W

$L_{arm}= 10^8 m$

Interferometric measurement system

Requirement $\delta x = 10^{-16}\, m/\sqrt{Hz}$ 0.01 Hz to 1 Hz

1) Transfer function

2) Shot noise

3) Relative intensity noise (RIN)

4) Frequency noise

5) Optical Pathlength

6) Phasemeter

Noise caused by fluctuations in the emitted laser power

Requirement:

$RIN = 3 \cdot 10^{-9}$ at MHz

Interferometric measurement system

Requirement $\delta x = 10^{-16}\, m/\sqrt{Hz}$ 0.01 Hz to 1 Hz

1) Transfer function

2) Shot noise

3) Relative intensity noise (RIN)

4) Frequency noise

5) Optical Pathlength

6) Phasemeter

Noise caused by fluctuations in the frequency of the laser

- Stabilised laser (Cavity)
  $\delta\nu = 5\, Hz/\sqrt{Hz}$
- Time delay interferometry (TDI)
  $L_{range} = 1\, cm$

Interferometric measurement system

Requirement $\delta x = 10^{-16}\, m/\sqrt{Hz}$ 0.01 Hz to 1 Hz

1) Transfer function

2) Shot noise

3) Relative intensity noise (RIN)

4) Frequency noise

5) Optical Pathlength

6) Phasemeter

Noise caused by fluctuations in the pathlength in the optical bench

(mainly thermal)

$\delta T = 0.1\, \mu K/\sqrt{Hz}$

Resolution of the phasemeter

$\delta \phi = 10^{-9}\, rad/\sqrt{Hz}$

Drag-free mass (Acceleration noise)

$$\delta a = 10^{-18}\, m/s^2\sqrt{Hz}$$

1) Thermal Radiation

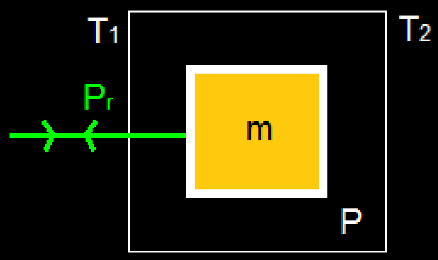
2) Radiation Pressure

3) Radiometer

4) Earth Gravitational Field

5) Electromagnetic fields

6) Actuators



Requirements:

$$m = 7\ Kg$$
$$l = 7cm$$

$$P_r = 50\ mW$$
$$RIN(10mHz) = 10^{-8}$$

$$\delta T = 0.1\mu K/\sqrt{Hz}$$
$$T = 293\ K$$
$$P = 3 \cdot 10^{-7} Pa$$

Drag-free mass (Acceleration noise)

$$\delta a = 10^{-18}\, m/s^2\sqrt{Hz}$$

1) Thermal Radiation

2) Radiation Pressure

3) Radiometer

4) Earth Gravitational Field

5) Electromagnetic fields

Earth Gravitational fields is negligible at the frequency range

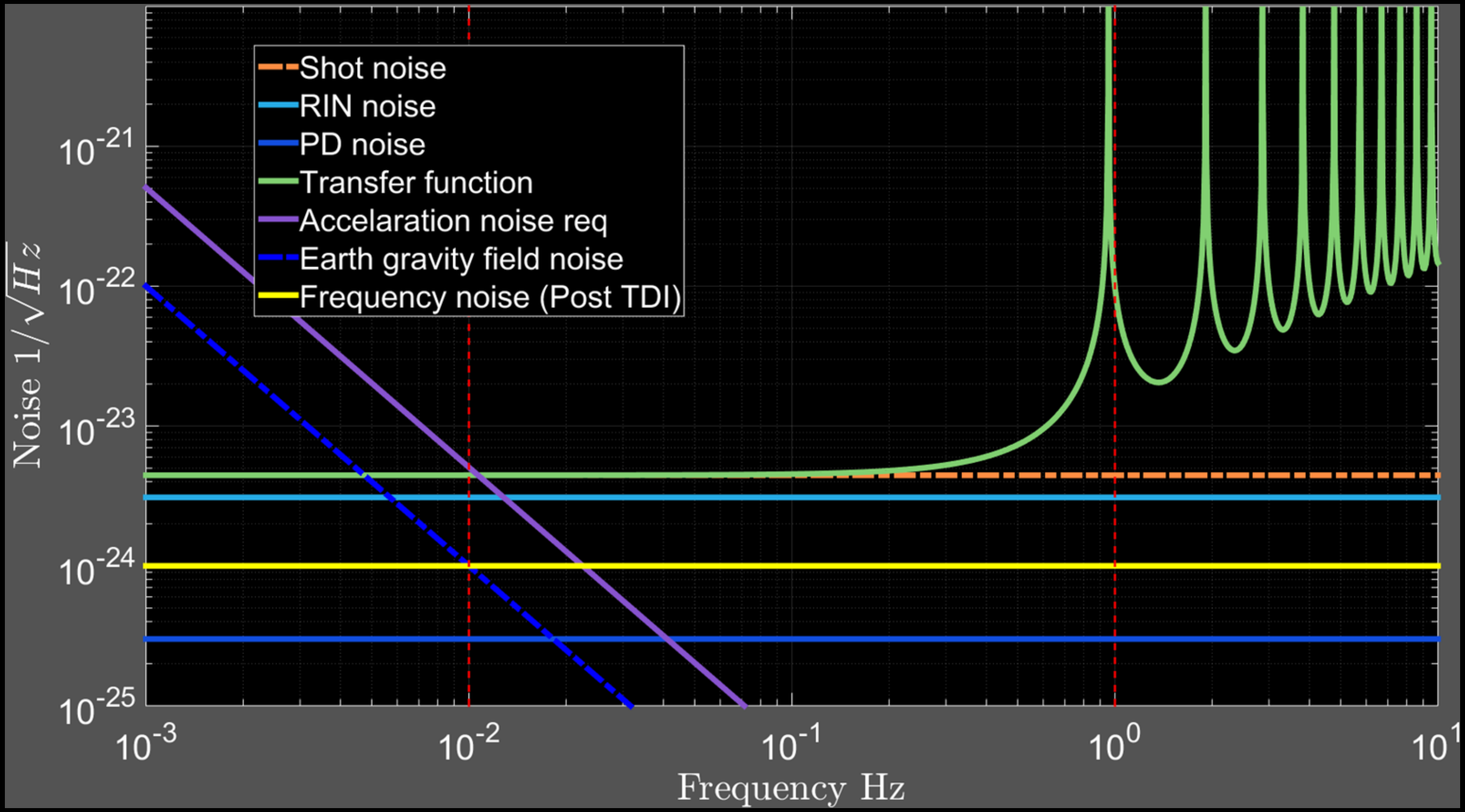
$$\chi_{mag} = 10^{-7}, m_r = 10^{-7} A/m^2$$

$$\delta B = 0.07 nT/\sqrt{Hz}$$

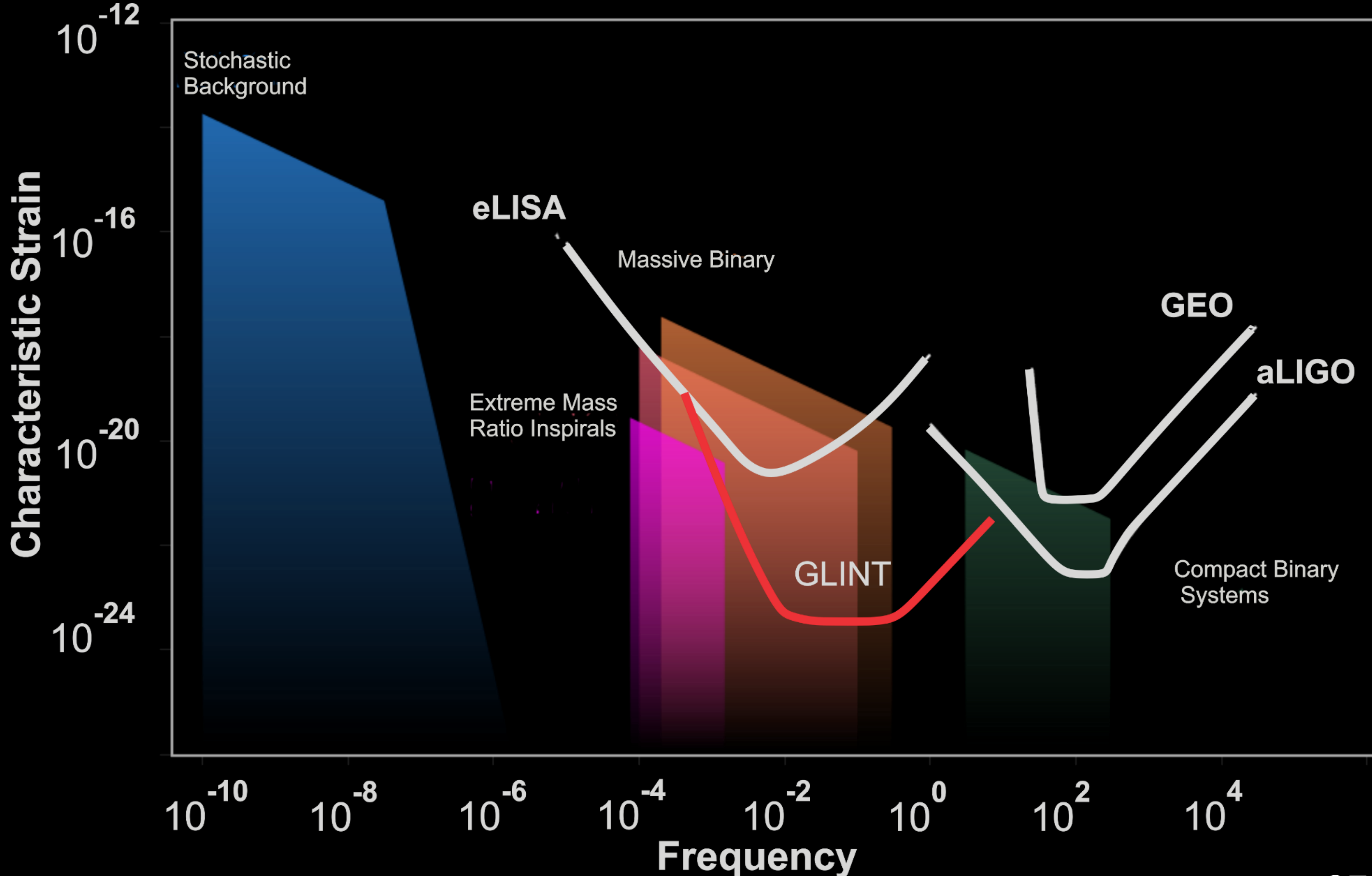
6) Actuators

Actuators frequency range shifted from the measurement band

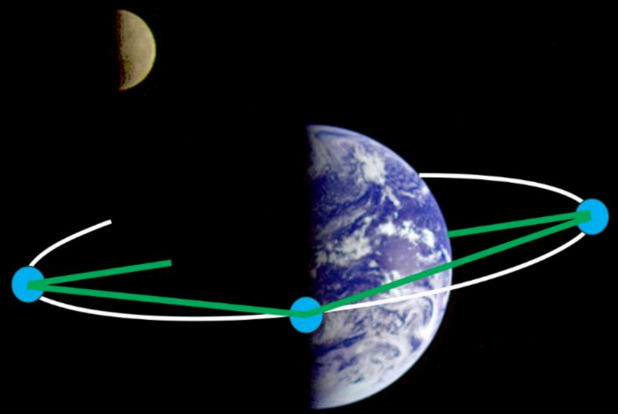
Sensitivity



Sources and observatories



Mission Design



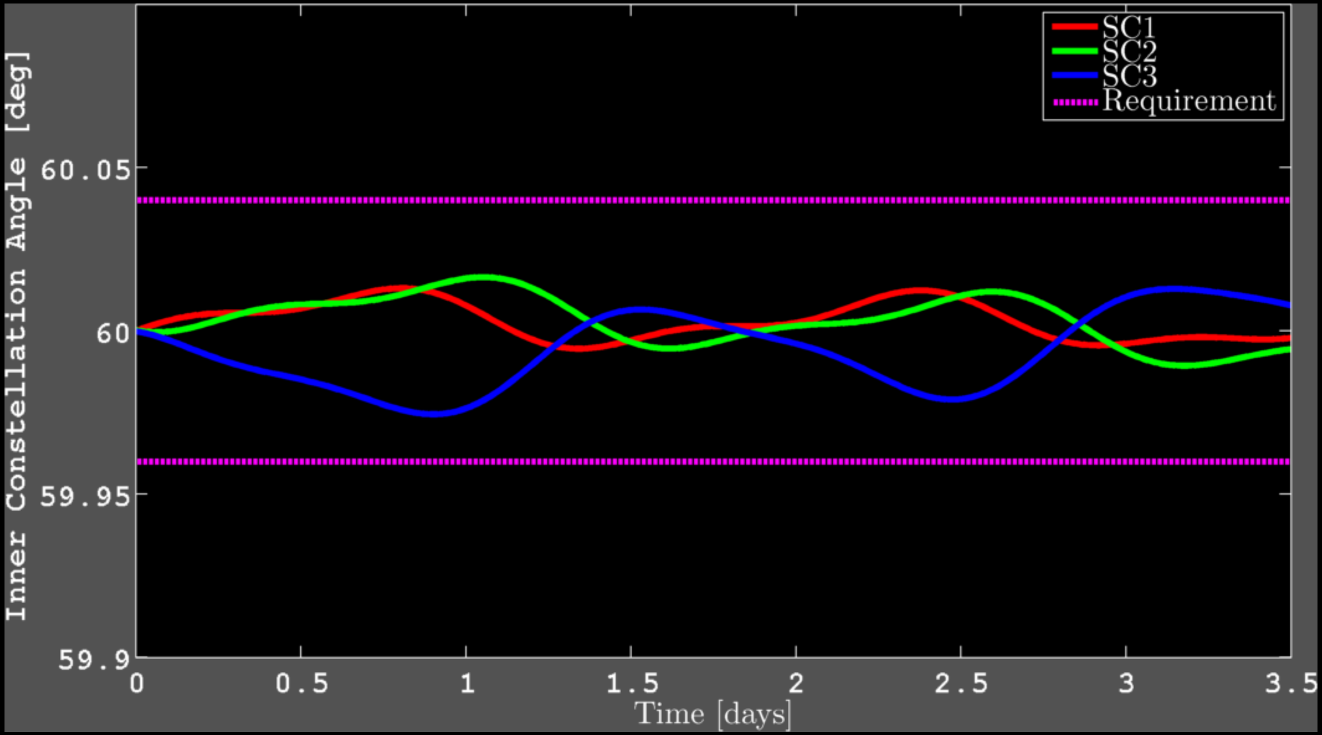
Orbit information

System Drivers:

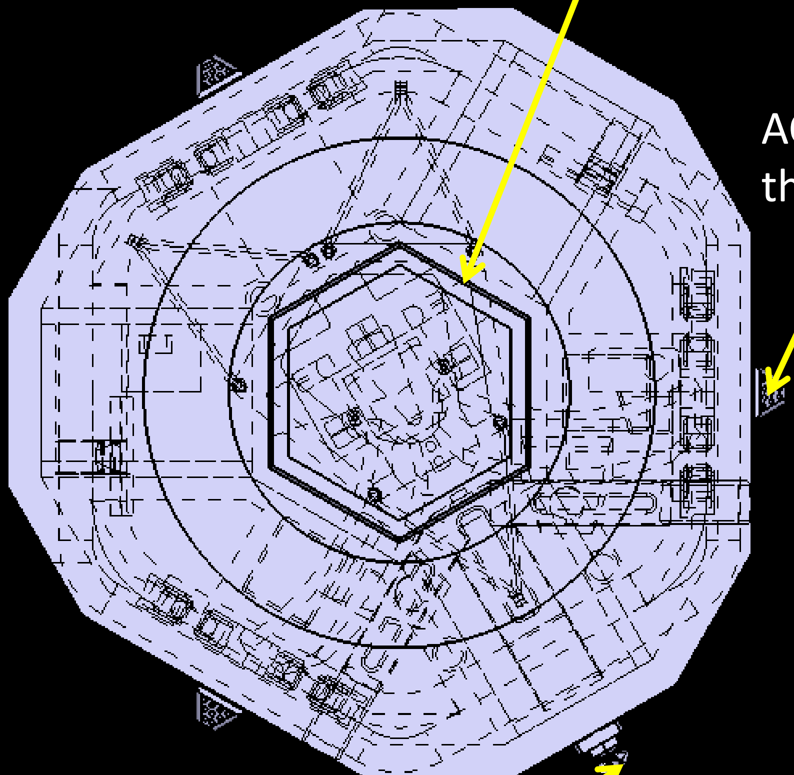
- 3 Satellites in plane
- Constant distance between all satellites: 100,000 km
- Minimum stray light and sun incidence onto telescopes
- Fixed telescopes (breathing angle: $\pm 0.04°$)

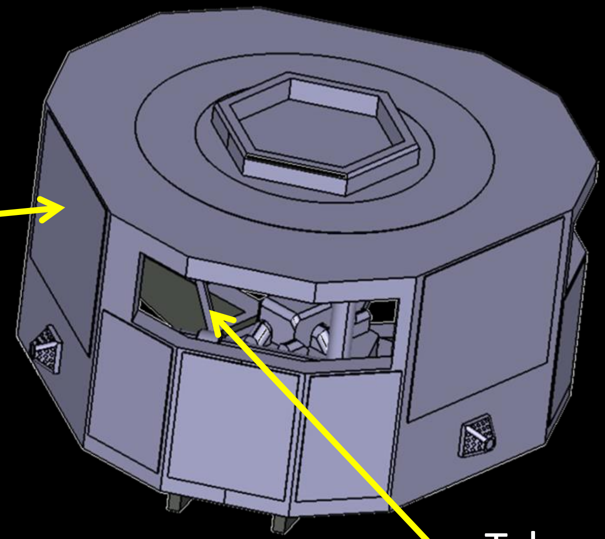
Satellites	**Glint 1; Glint 2; Glint 3**
Semi-major Axis	57.735 km
Eccentricity	0 (circular)
Inclination	12°

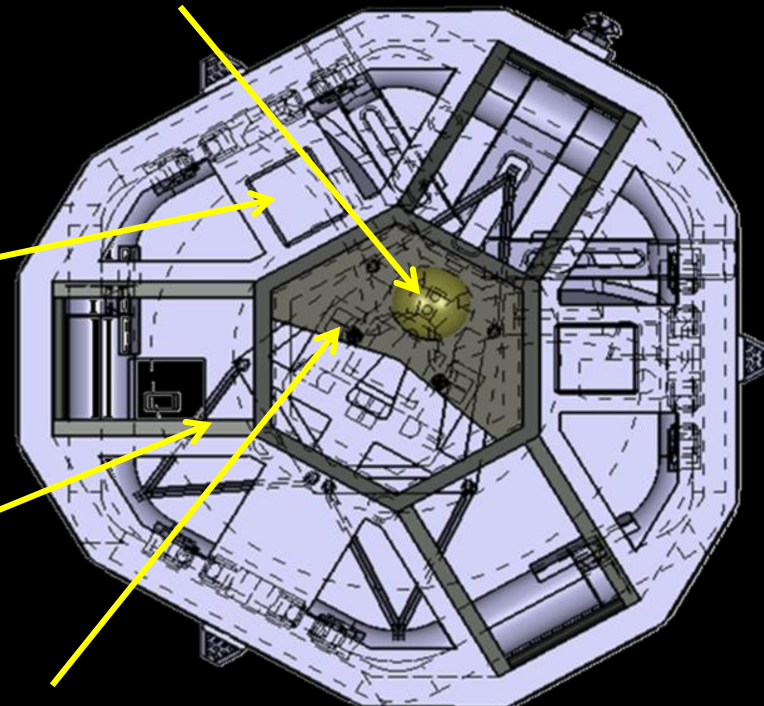
Orbit information



Spacecraft

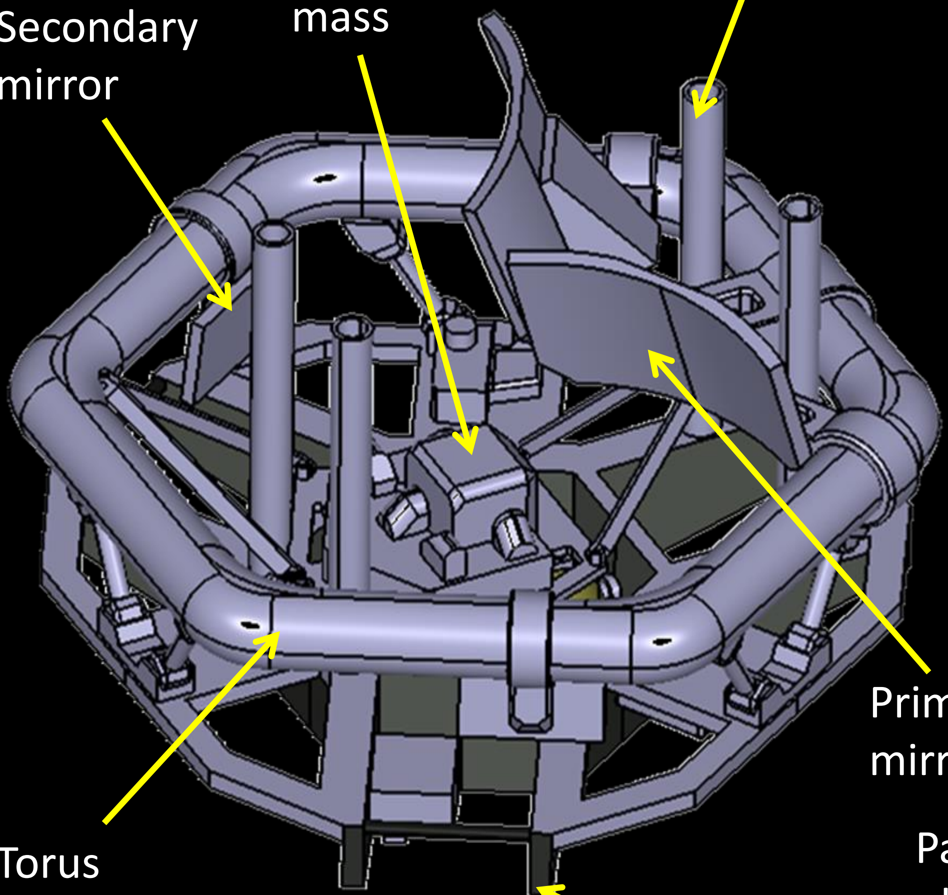


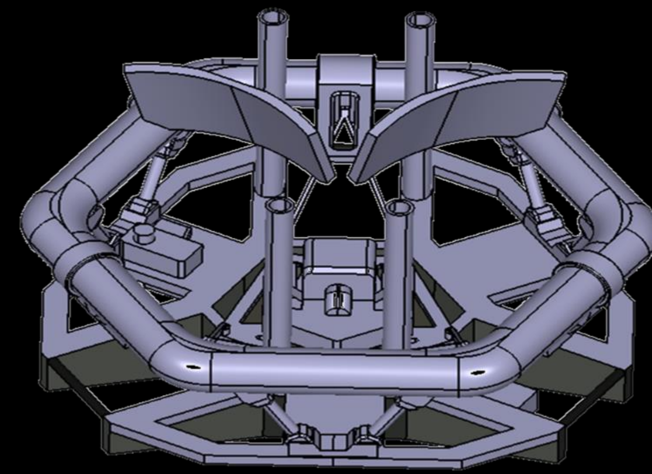


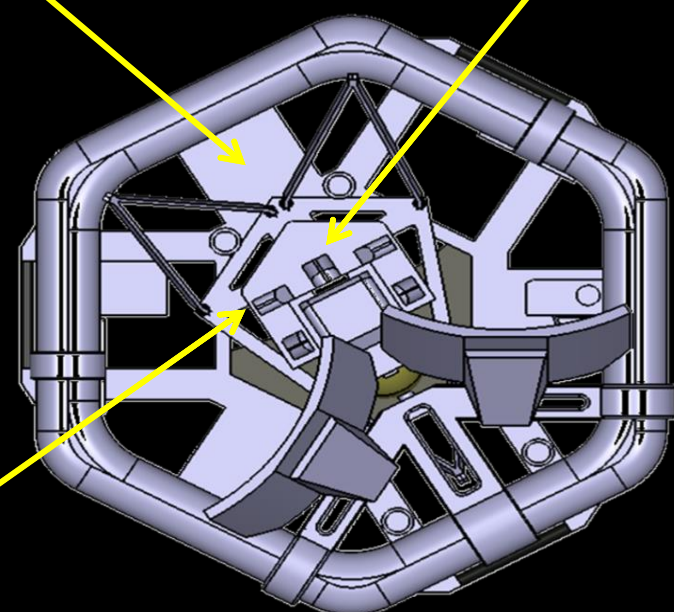


Diameter = 4.5 m
Height = 3 m

Payload


Compression cylinders
Test mass
Secondary mirror
Primary mirror
Torus
Main frame




Main plate
Optical bench
Payload platform

Mass budget

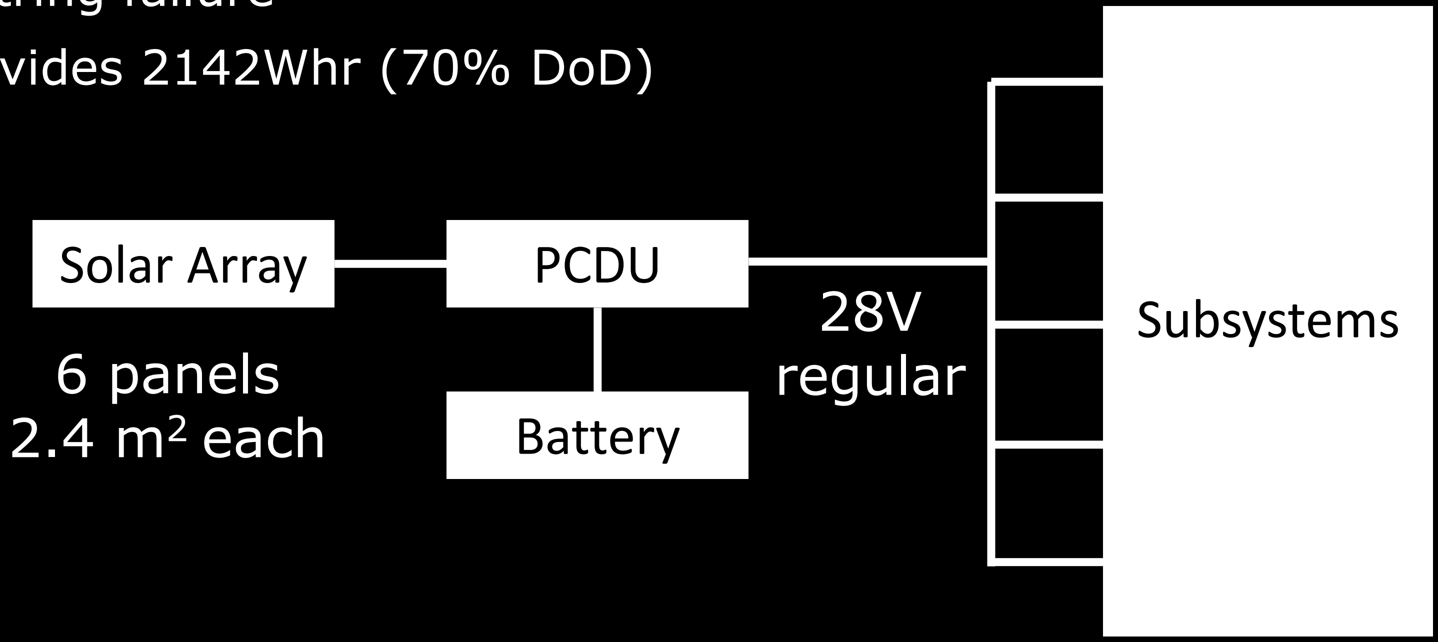
Subsystem	Mass (kg)
Thermal	26
Communications	17
Payload	627
Propulsion	193
Power	187
Structure	362
AOCS	47
Data Handling	47
20% system margin included	
Total dry mass	1506
Propellant	75
TOTAL MASS	1581

Power budget

Subsystem	Power Consumption (W)
Laser	300
Rest of system	50
Payload total	**350**
Propulsion	182
AOCS	50
Thermal Control	300
Communications	20
Data Handling	63
Platform total	**665**
Required power	965
System margin 20%	193
TOTAL POWER	**1158**

Power architecture

- Li-Ion batteries sized for eclipse of 70 minutes
- 1 string failure
- Provides 2142Whr (70% DoD)



Thermal subsystem

Payload requires thermal stability at 0.1 μK at 10^{-2} Hz

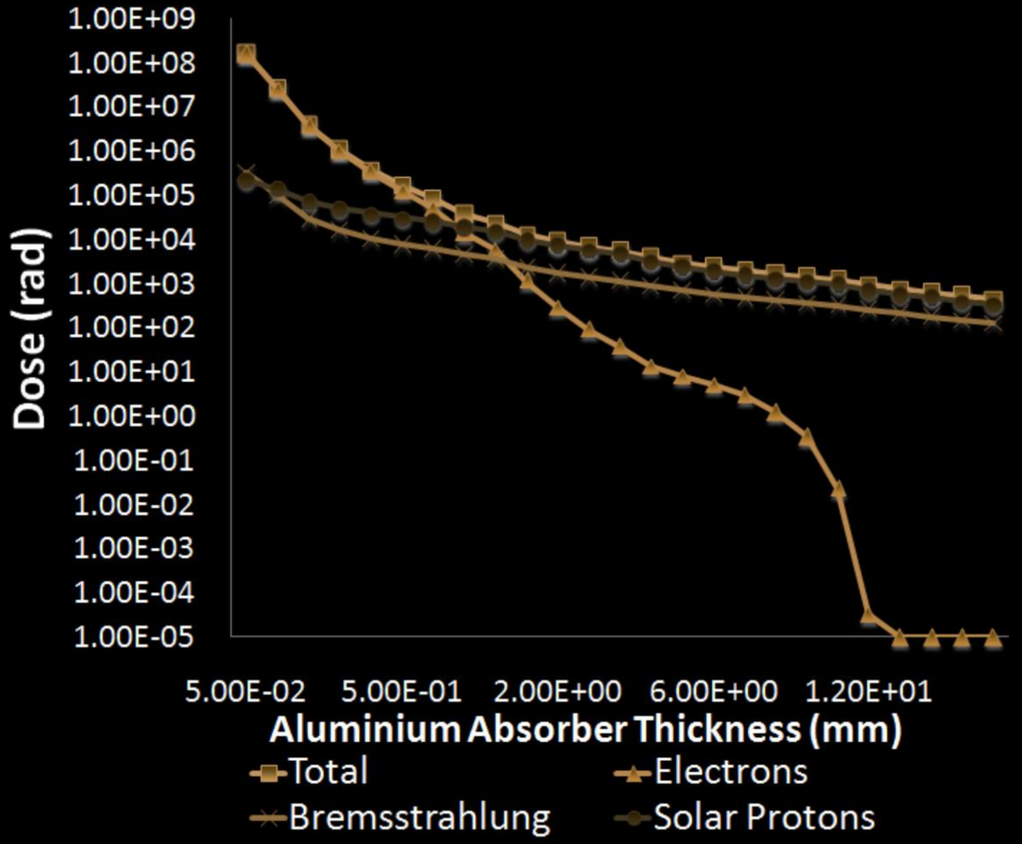
- Stability

$$T = 10^{-8}\sqrt{1+\left(\frac{20\ mHz}{f}\right)^4}\ in\ K$$

- **Passive control** interface to optical bench ($10^{-5}\ K$) sufficient
  - Maintained with multi layer insulation system for rest of satellite
  - High emissivity surfaces so most thermal energy radiated to space
  - Thermistors and thermocouples used to monitor the temperature.

Radiation shielding

- Non critical subsystem
  - Close to GEO (mature technology)
  - Short life time (3 years vs 15 years)



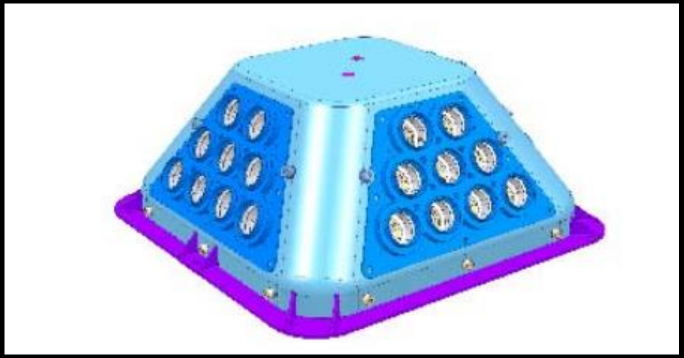
Propulsion

System Drivers

- Drag Free control to reduce outside disturbances
- Full 3 – axis control
- Thrust Precision: 0.5μN
- Thrust Noise: $0.1\mu N/Hz^{1/2}$

Chosen Design

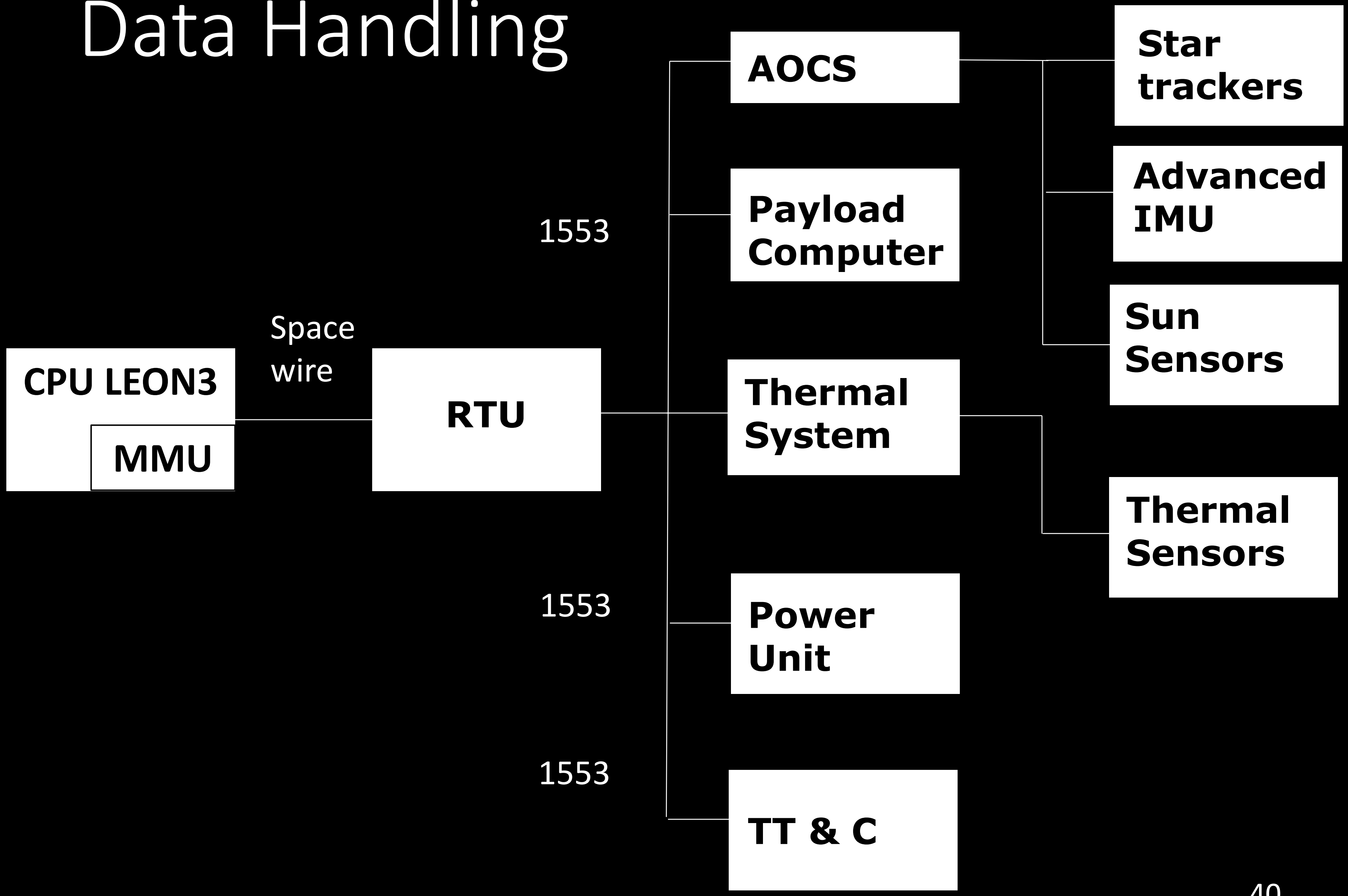
- 3 Cluster of **FEEPS** (Indium)
- ISP: 4000 – 8000 s
- Thrust Precision: 0.1μN
- Thrust Noise: $<0.1\mu N/Hz^{1/2}$
- Thrust response: 0.1 ms



Attitude Control System

	Spacecraft	Laser beam
Pointing accuracy	350 μrad (half of breathing angle)	100 nrad (derived from the strain curve)
Sensing	1 Star tracker (3 heads) 2 Sun Sensor 1 Advanced IMU	Differential wave front sensing
Actuators	3 FEEPs	Steerable mirror

Data Handling



Communication

System Drivers

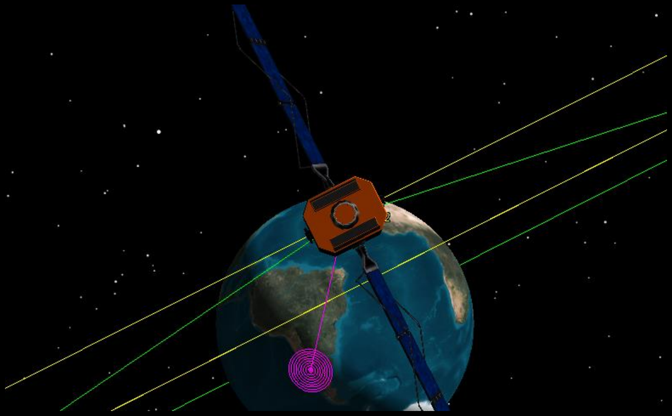
- Data volume per day per spacecraft: 1.8 GB
- Communicate without re-orientating the spacecraft
  - Non critical system

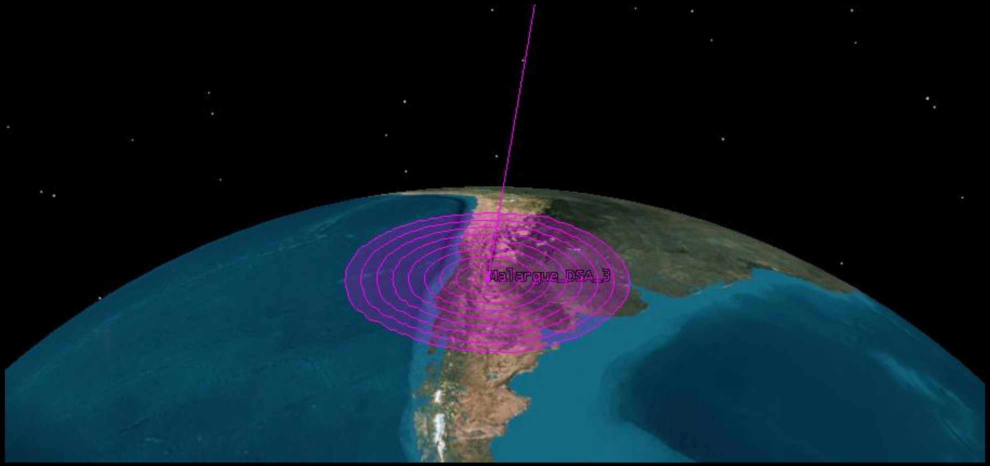
System			
Frequency band	X – band (8.45 GHz)	Downlink time	2 hours per satellite
Antenna type	Patch (3x)	Downlink rate	2048 kbit/s
	Low gain	Contact	Every 3rd day

- The calculated Link Budget with final Link Margin: 8.77 dB

Ground station

35 m Deep Space Antenna 3 in Malargüe, Argentina - X band

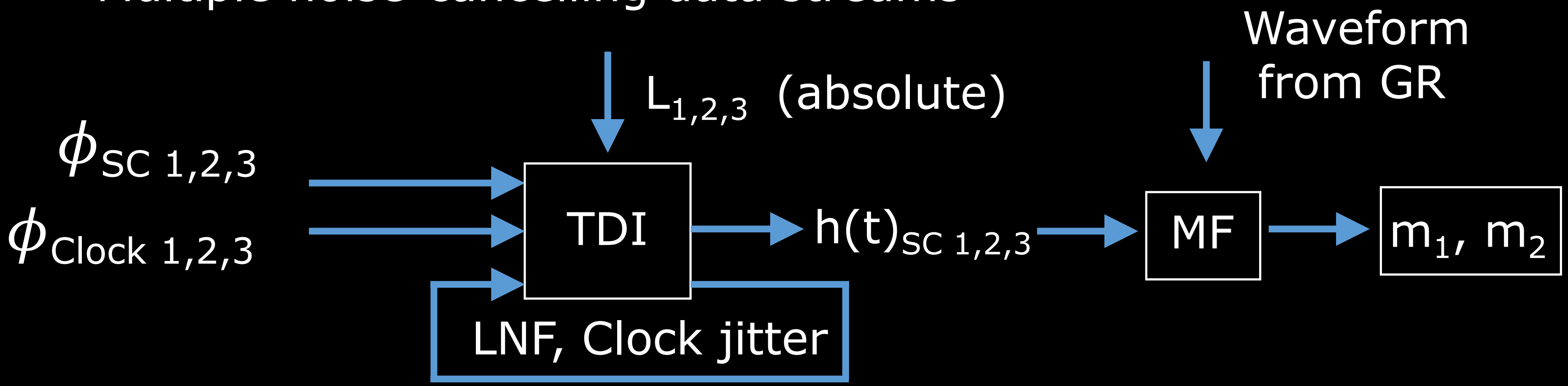




Post Processing

To retrieve the GW signal from the measurement

- TDI (Time delay interferometry) cancels laser frequency noise (LFN) and clock jitter by combining the phase measurements made at different times and spacecraft
- Matched filtering (MF) recovers source parameter from expected waveforms
- Multiple noise-cancelling data streams



Launch & EOL

Required payload insertion

3 x 1581 kg

Circular orbit

Radius 57735 km

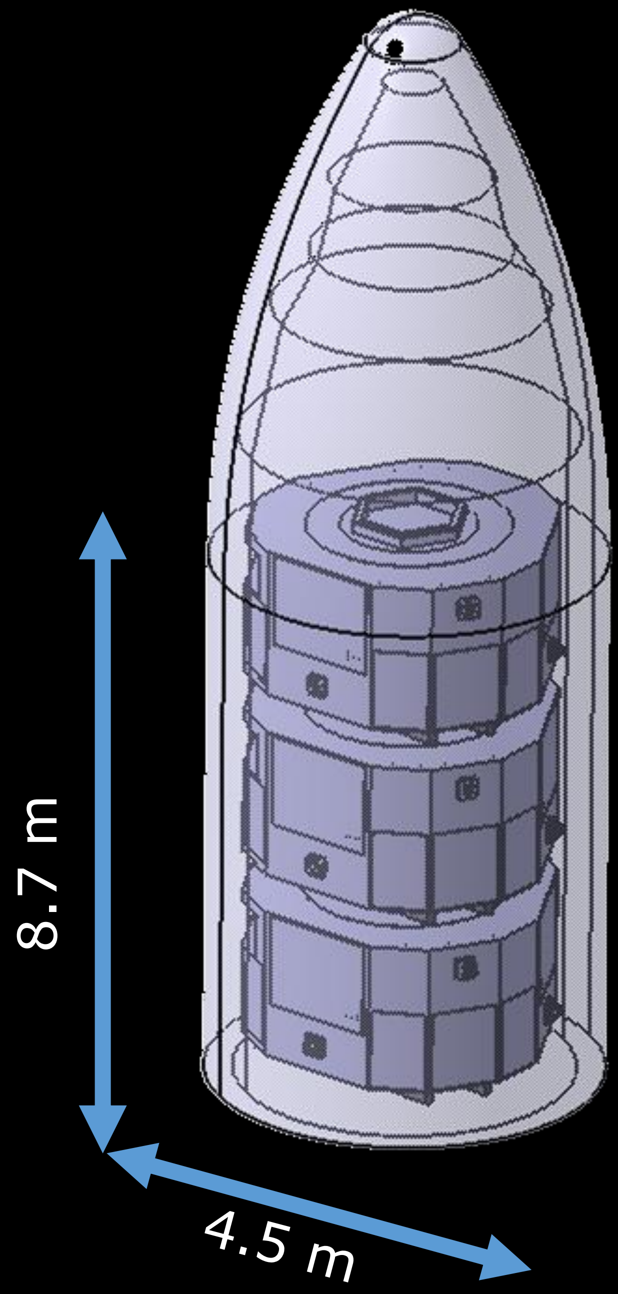
Launch mass is compatible with

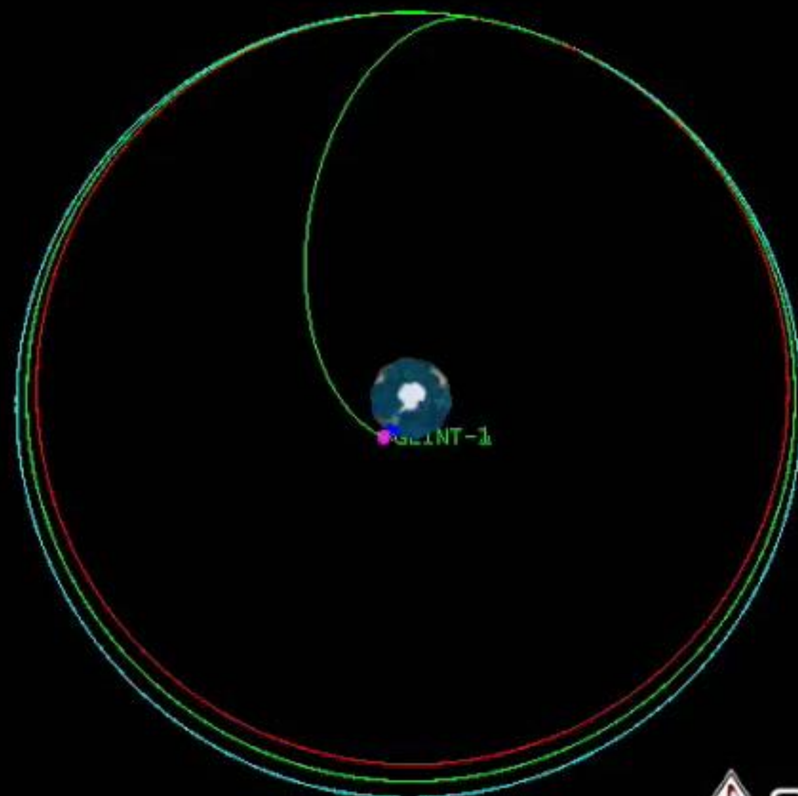
Ariane 5 ECA

Falcon Heavy

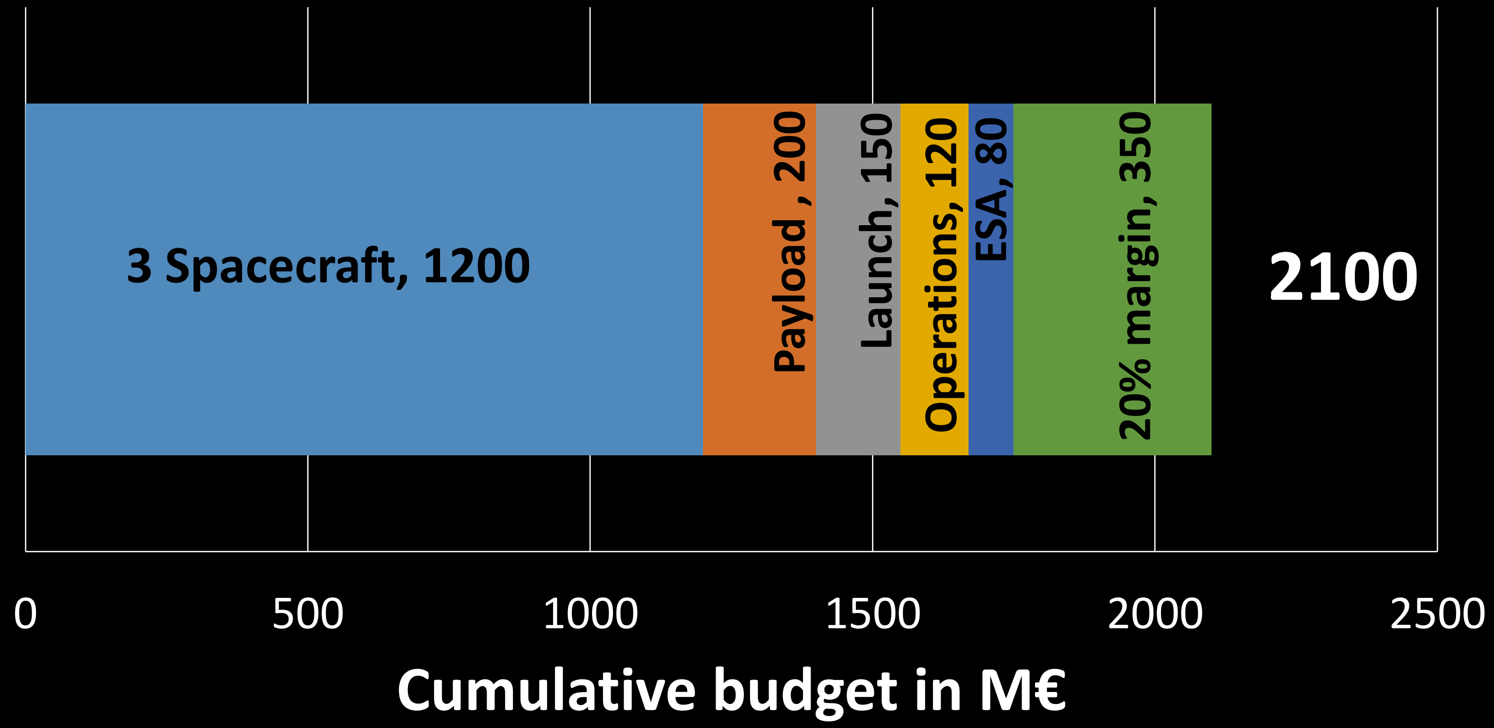
End of life

Beyond GEO - No action required





Financial budget



Risk Mitigation

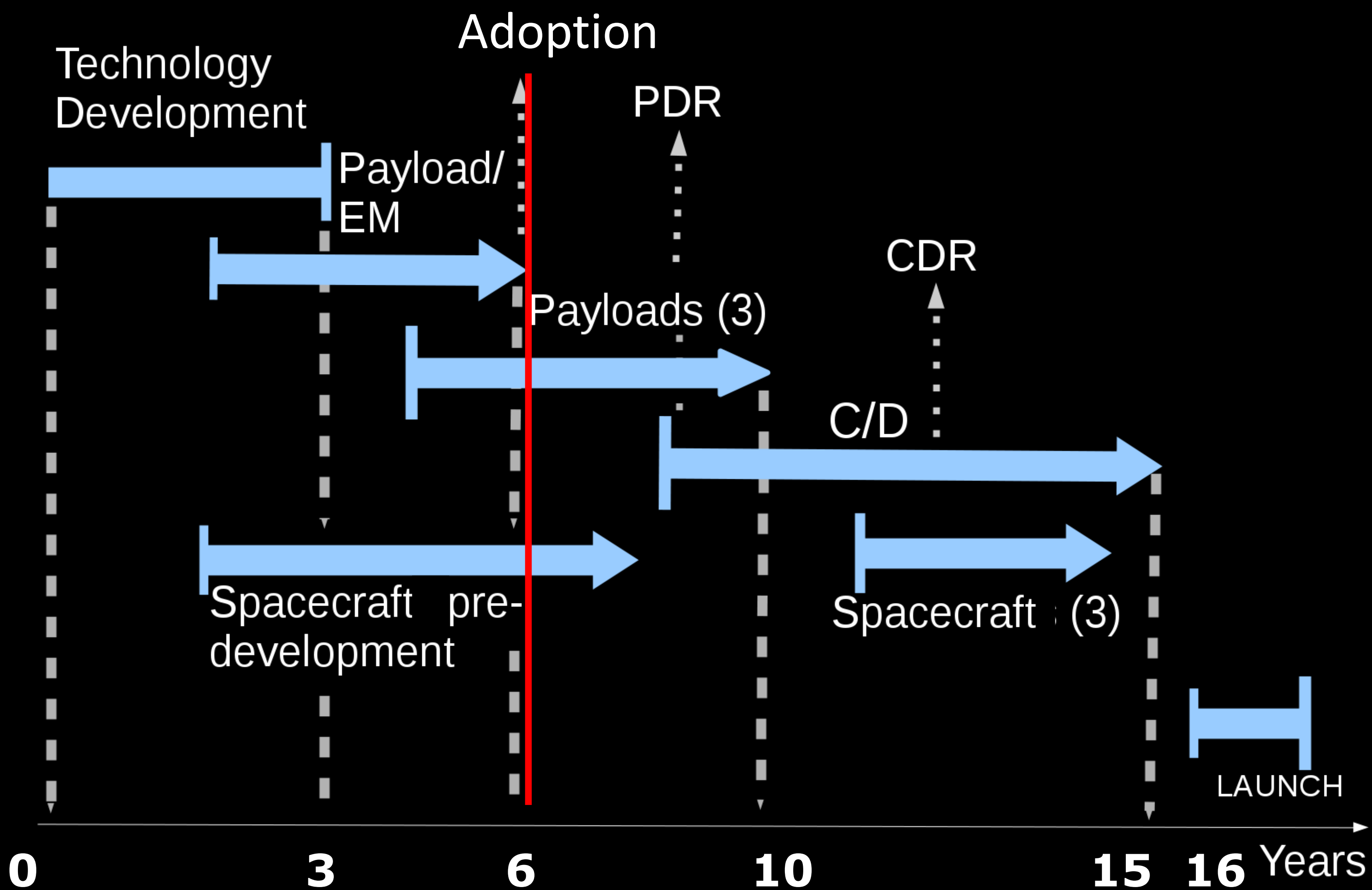
a	Test Mass Failure
b	Performance
c	Acceleration Noise Spec not met
d	Laser Noise
e	Phase Meter

		Consequence				
Likelihood		**Minor**		**Major**		**Catastrophic**
	very likely					
				c		
	likely			**b,e**		
					a	
	unlikely			**d**		

Technology Development

Area	Item	Challenge	Heritage	TRL
Payload	Phasemeter	Improvement of 3 order of magnitude	LPF, LISA	3
	Telescope	Larger mirrors	GAIA	4
	Optical bench	Placement of components, manufacturing	LPF, LISA	4
	Test mass read out, caging	Reliable caging/ launch look, optical read out	LPF, LISA	3-4
	50 W Laser	Space qualification	iPG potonics	4
Platform	Indium FEEP Thrusters and Control Algorithm	Qualification and Delta control from LISA	LISA/ Seibersdorf	3-4

Timeline


Adoption
Technology Development
PDR
Payload/ EM
CDR
Payloads (3)
C/D
Spacecraft pre-development
Spacecraft (3)
LAUNCH
0
3
6
10
15
16
Years

GLINT of the future

- Public Outreach

  European Citizens:

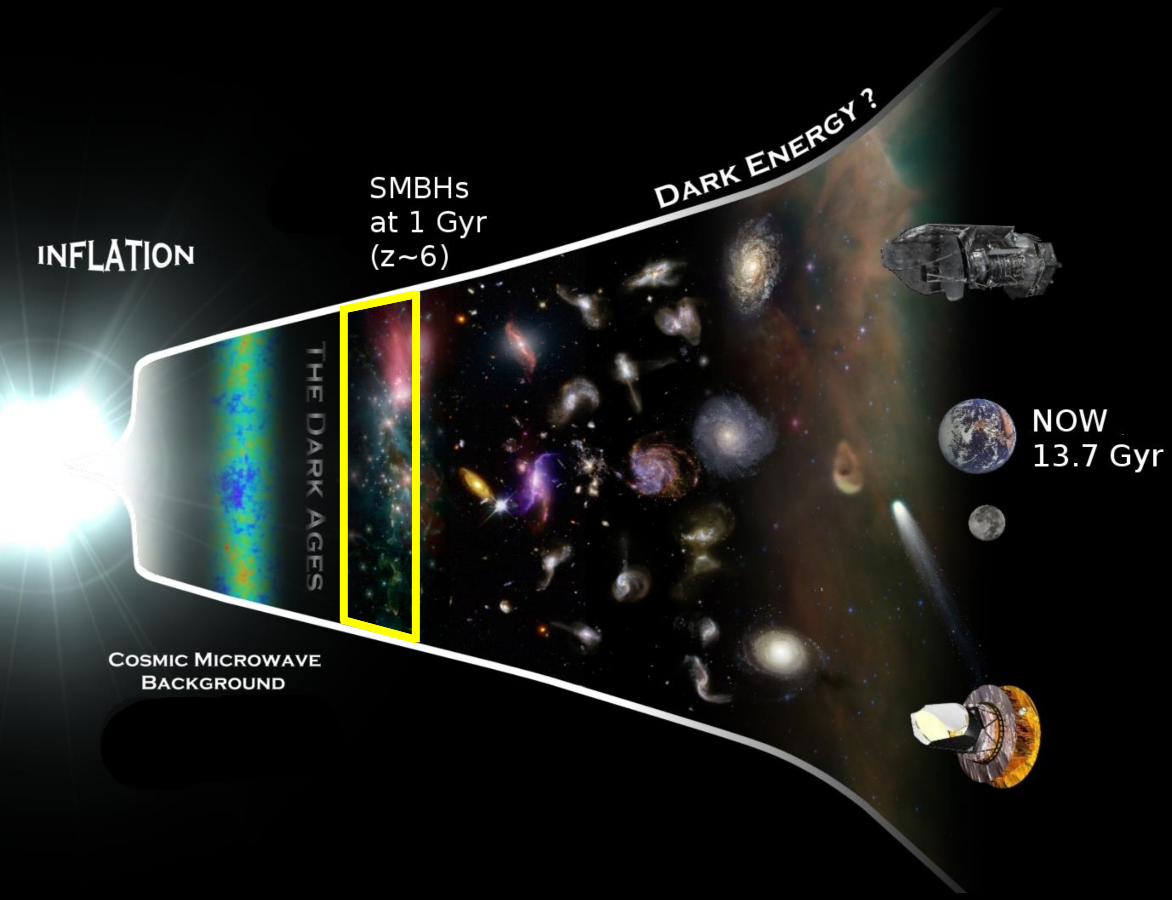
  - Naming of satellites
  - Improvement on technologies
  - Lead international research in gravitational wave and contribute to the cutting edge of fundamental physics

  Shape the Youth:

  - Experimental setups using lasers and/or optics.
  - Peak interest into astronomy for the future
  - G-man, exploring the universe with his laser eyes

G-MAN

Summary



INFLATION
Cosmic Microwave
Background
The Dark Ages
SMBHs
at 1 Gyr
(z~6)
Dark Energy ?
NOW
13.7 Gyr

Backup Slides

- “What an awesome spacecraft cowboy!” Glint Eastwood
- “This spacecraft is a real atomic bomb!” Robert Oppenheimer
- “Glint is even better than a good cup of tea!” Queen Elizabeth

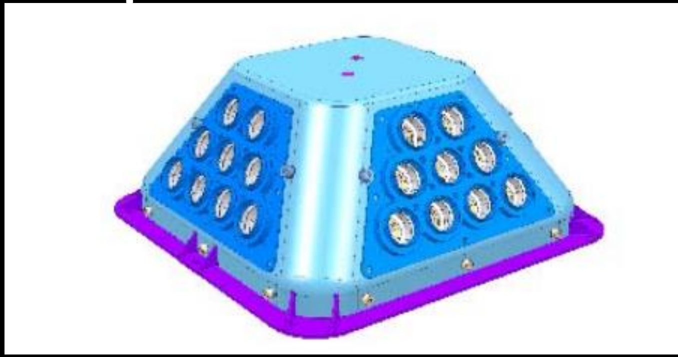
GW Detection Discarded Options

- Atomic Clocks and Atomic interferometers
  Space Based technology not mature. Very Promising in the next years

- Bose Einstein Condensates
  Very innovative but at the moment is only a theoretical study

- Squeezed Light
  Promising but is required further experimental studies for space-based applications

Indium FEEP Micropropulsion



Thruster requirements:

- Minimum Thrust 0.3 µN (Target 0.1 µN)
- Maximum Thrust 100 µN (Target 150 µN)
- Total Impulse 2920 Ns (Target 4000 Ns)
- Thrust Noise < 0.1 µN/Hz
- Thrust Resolution 1 µN
- Specific Impulse > 4000 s

Size: Ø∼10 cm; L~10 cm
Mass: 300g thruster +1kg PCU
Power: 7 W (heater)

Performance values for a single In-FEEP emitter:

- Thrust 0.1 – 15 µN / Emitter
- Thrust Resolution < 0.1 µN
- Thrust Noise < 0.1 µN/√Hz
- Minimum Impulse Bit < 5 nNs
- Total Impulse 490 -1000 Ns / Emitter
- Specific Impulse 4000 - 8,000 s

Science objectives	Science Investigation	Reference measurements	Instruments requirements
Direct collapse black holes detection in the range of 10E4 to10E6 solar masses	h=10E-23 (1/sqrt(Hz)) f= 0.01-0.1Hz 10 to 100s Rate: 10000/year	Laser Interferometry – Distance measurement between three free floating masses in space (phase measurement)	Acceleration Noise < 10E-18 m/(s^2*sqrt(Hz) Dx<10^-16m/sqrt(Hz) Resolution phasemeter DPhi< 10E-9 rad/sqrt(Hz) Thermal stability of the TM DT < 100nK/sqrt(Hz) Magnetic Shielding DB<0.07nT/sqrt(Hz) Relative intensity noise RIN Noise < 3*10-9 at MHz Frequency stability of the Laser <5Hz/sqrt(Hz) Time delay interferometry L_range< 1cm Test Mass Assembly m=7kg cube side=7cm Au-Pt Alloy T=293K dT <0.1*10E-6 K/sqrt(Hz) P=3*10E-7 Pa
The collapse of very massive Objects in the range 10E2 to 10E5 solar masses	h=10E-23(1/sqrt(Hz)) f= 0.01-0.02Hz Duration 10 to 100s Rate: 4000/year		
The collapse of super massive stars in the range of 260 to 800 solar masses	h=5*10E-24(1/sqrt(Hz)) F= 0.4-1Hz Duration 5 to 60s Rate: 10E7/year		
Two merging black holes in the range 10E2 to 10E5 solar masses	h=10E-23(1/sqrt(Hz)) F= 0.01-1Hz Duration 604800s Rate: 10E3/year		