



LISA  
CONSORTIUM

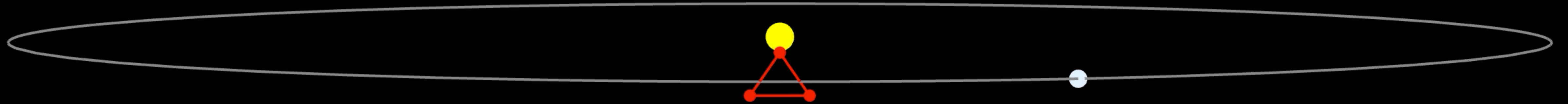
MAX PLANCK INSTITUTE  
FOR GRAVITATIONAL PHYSICS  
(ALBERT EINSTEIN INSTITUTE)



# Overview of the LISA detector and its future observational capabilities

GraSP24, 2024-10-23, Olaf Hartwig

# The Laser Interferometer Space Antenna (LISA)



- 3 spacecraft on **individual solar orbits**, arranged to stay in a quasi-equilateral triangle formation
- Symmetric laser links across 2.5 million km arm arms, measuring **pm scale** distance fluctuations between free-falling test masses (TM) housed in each spacecraft.
- LISA was officially adopted by ESA  $\implies$  💰, 🏗️, **planned launch ~ 2035**
- Details: <https://www.cosmos.esa.int/web/lisa/lisa-redbook>

# Why go to space?



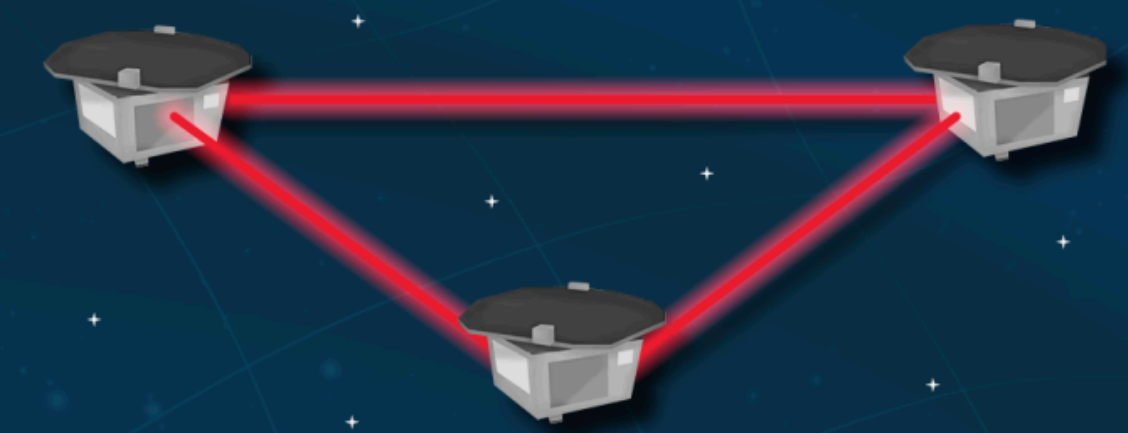
## THE SPECTRUM OF GRAVITATIONAL WAVES

Observatories & experiments

Ground-based experiment



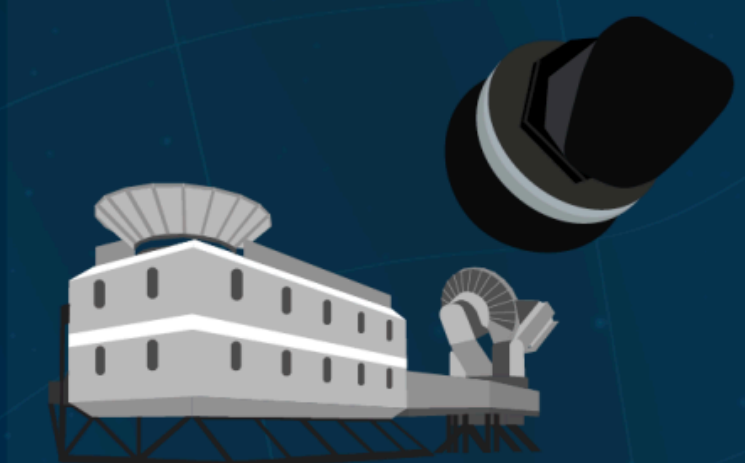
Space-based observatory



Pulsar timing array



Cosmic microwave background polarisation



Timescales

milliseconds

seconds

hours

years

billions of years

Frequency (Hz)

100

1

$10^{-2}$

$10^{-4}$

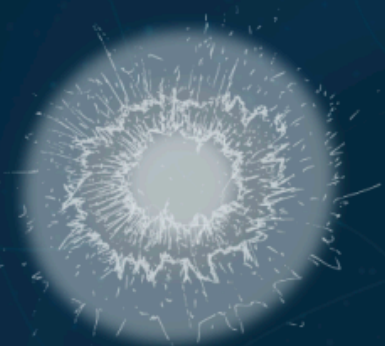
$10^{-6}$

$10^{-8}$

$10^{-16}$

Cosmic fluctuations in the early Universe

Cosmic sources



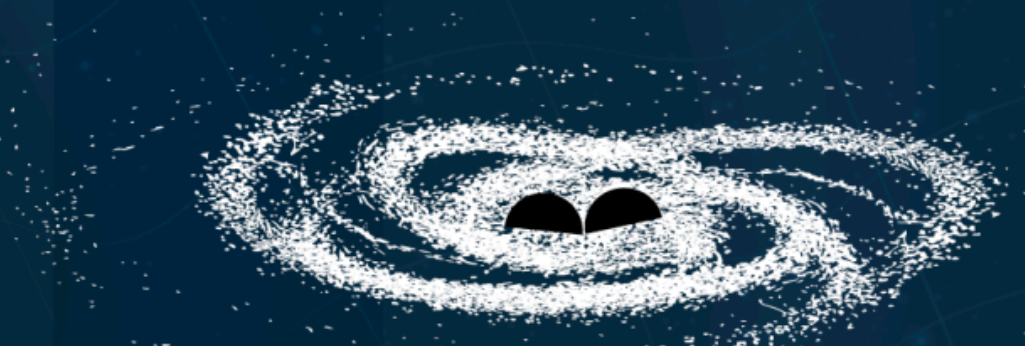
Supernova



Pulsar



Compact object falling onto a supermassive black hole



Merging supermassive black holes



Merging neutron stars in other galaxies



Merging stellar-mass black holes in other galaxies



Merging white dwarfs in our Galaxy

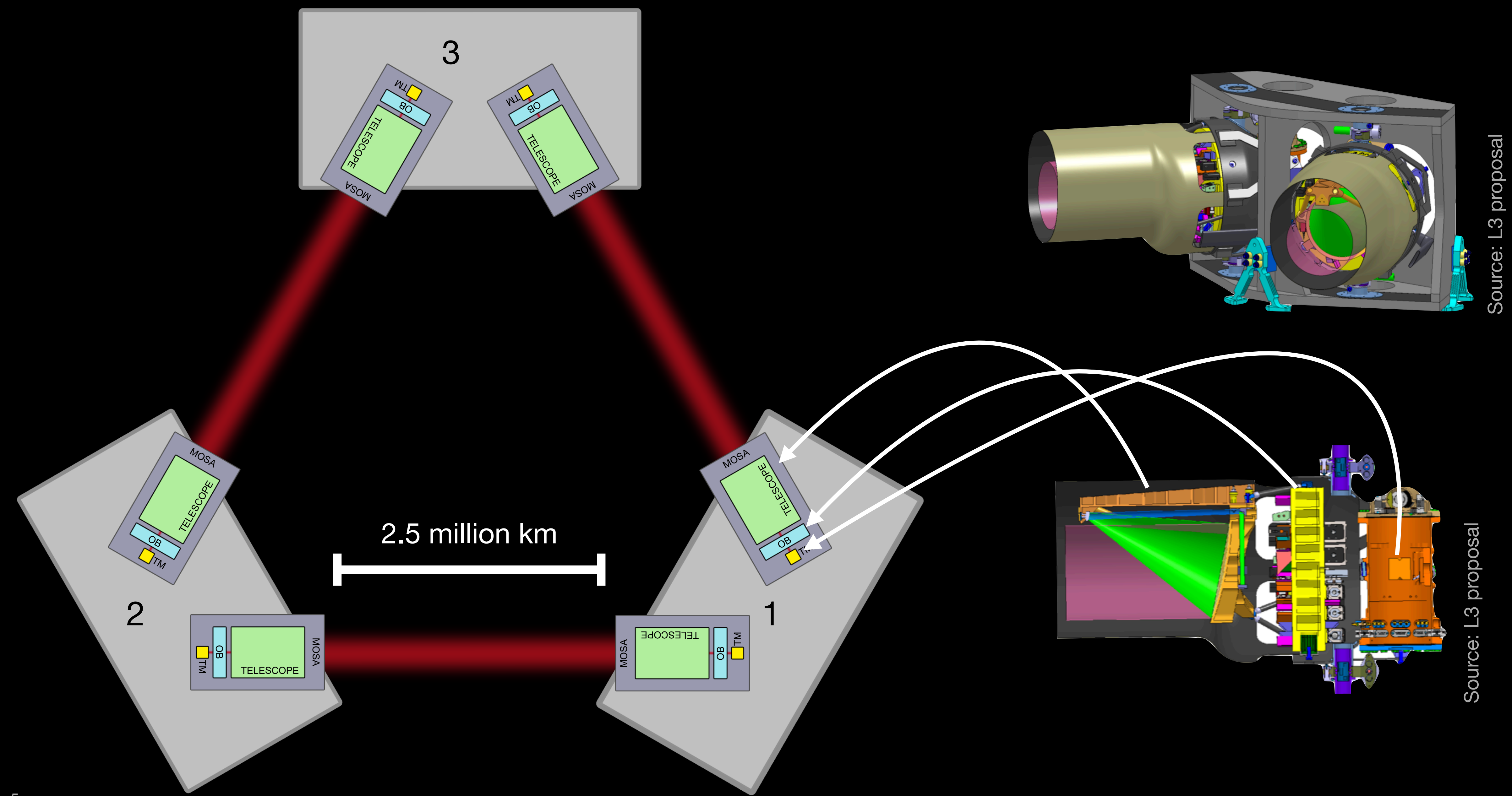


Source: LISA Redbook

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# Technical overview

# LISA constellation overview

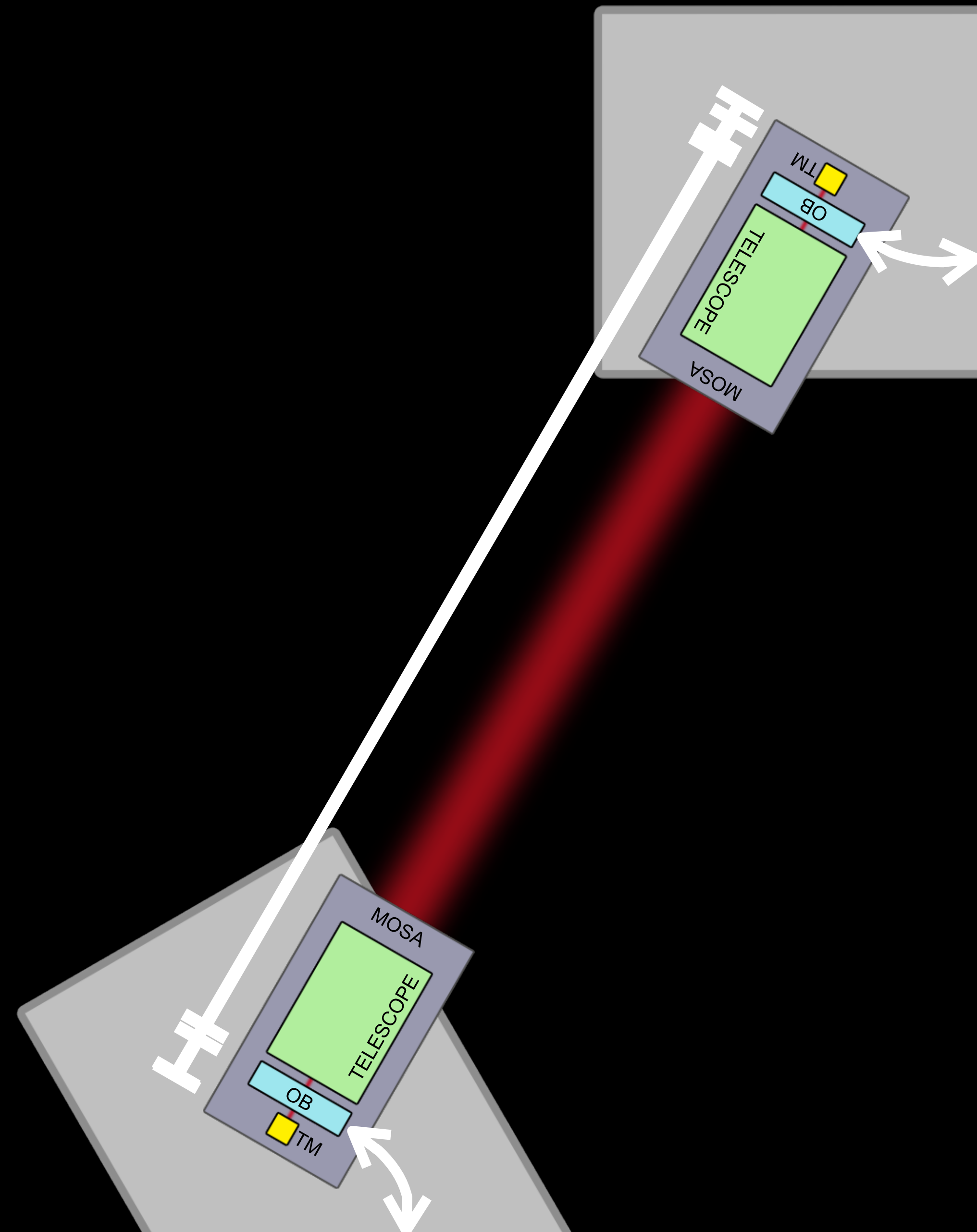


Source: L3 proposal

Source: L3 proposal

# LISA constellation overview

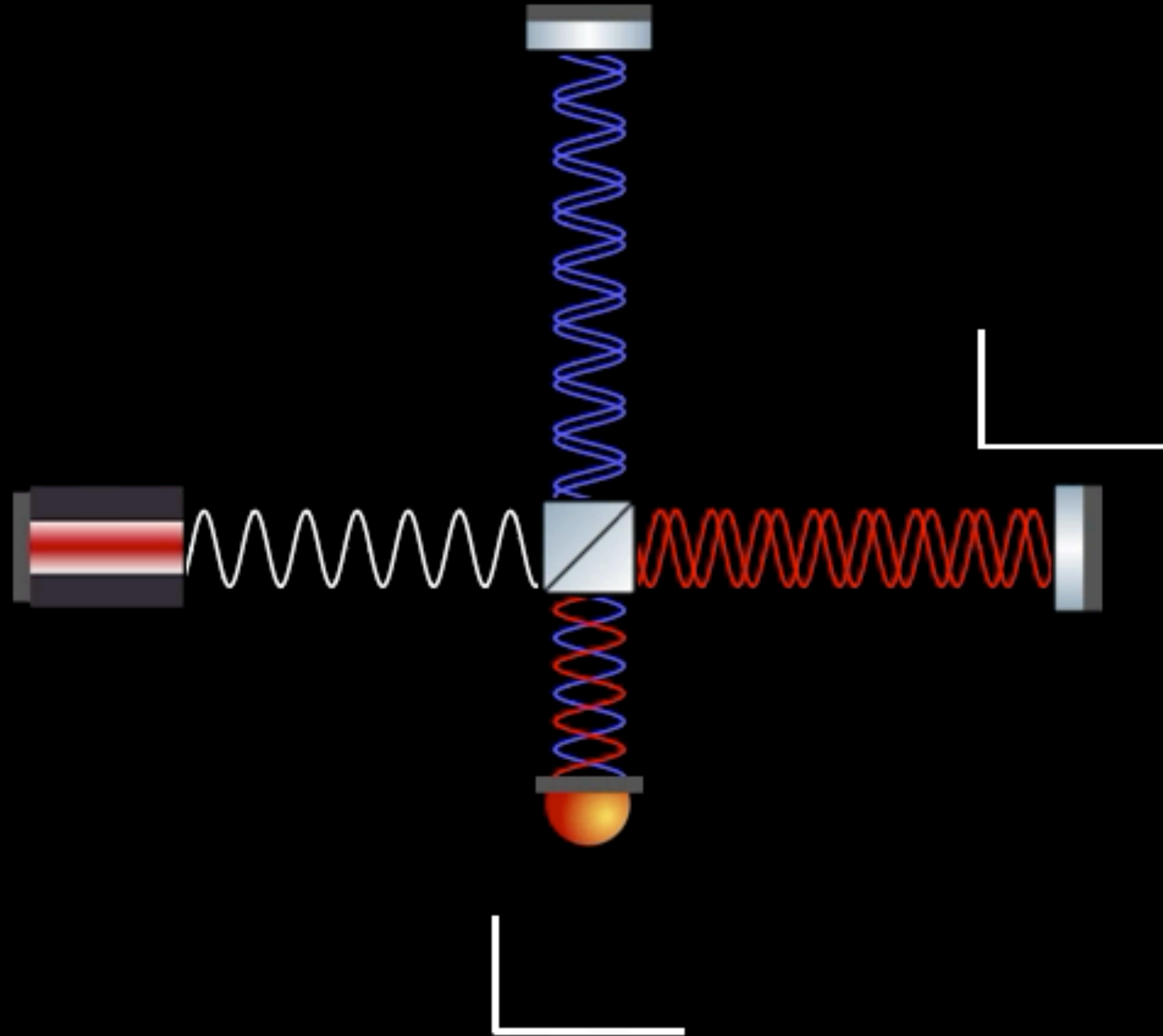
- Desired measurement: TM-TM
- 3 Interferometers on each optical bench (OB):
  - Science (SCI) interferometer
  - Testmass (TM) interferometer
  - Reference (REF) interferometer
- Combined in post-processing to construct single link, suppressing longitudinal S/C jitter
- However: some noise sources need suppression!



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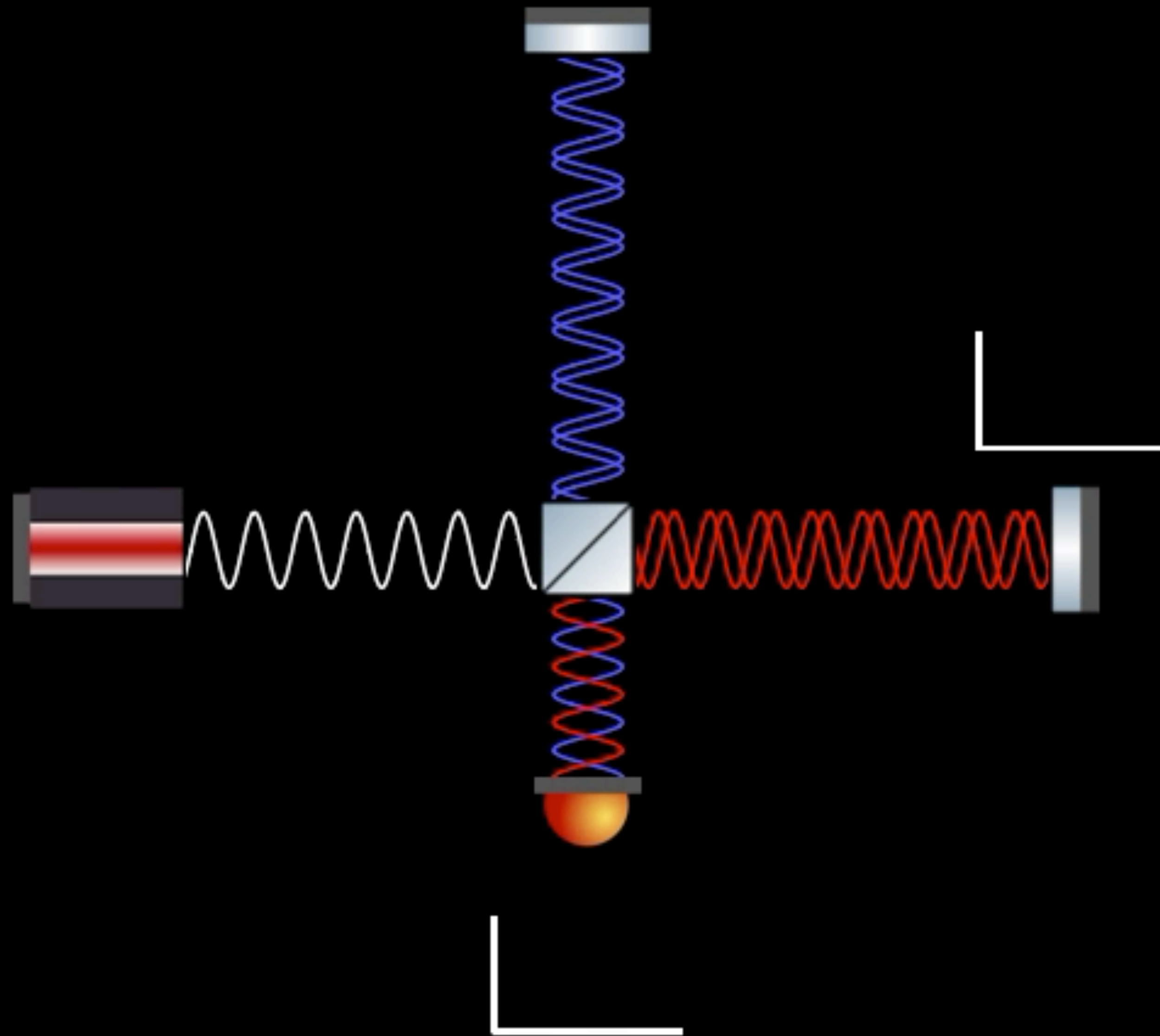
# Suppressed noise sources

# Laser noise cancellation in interferometers

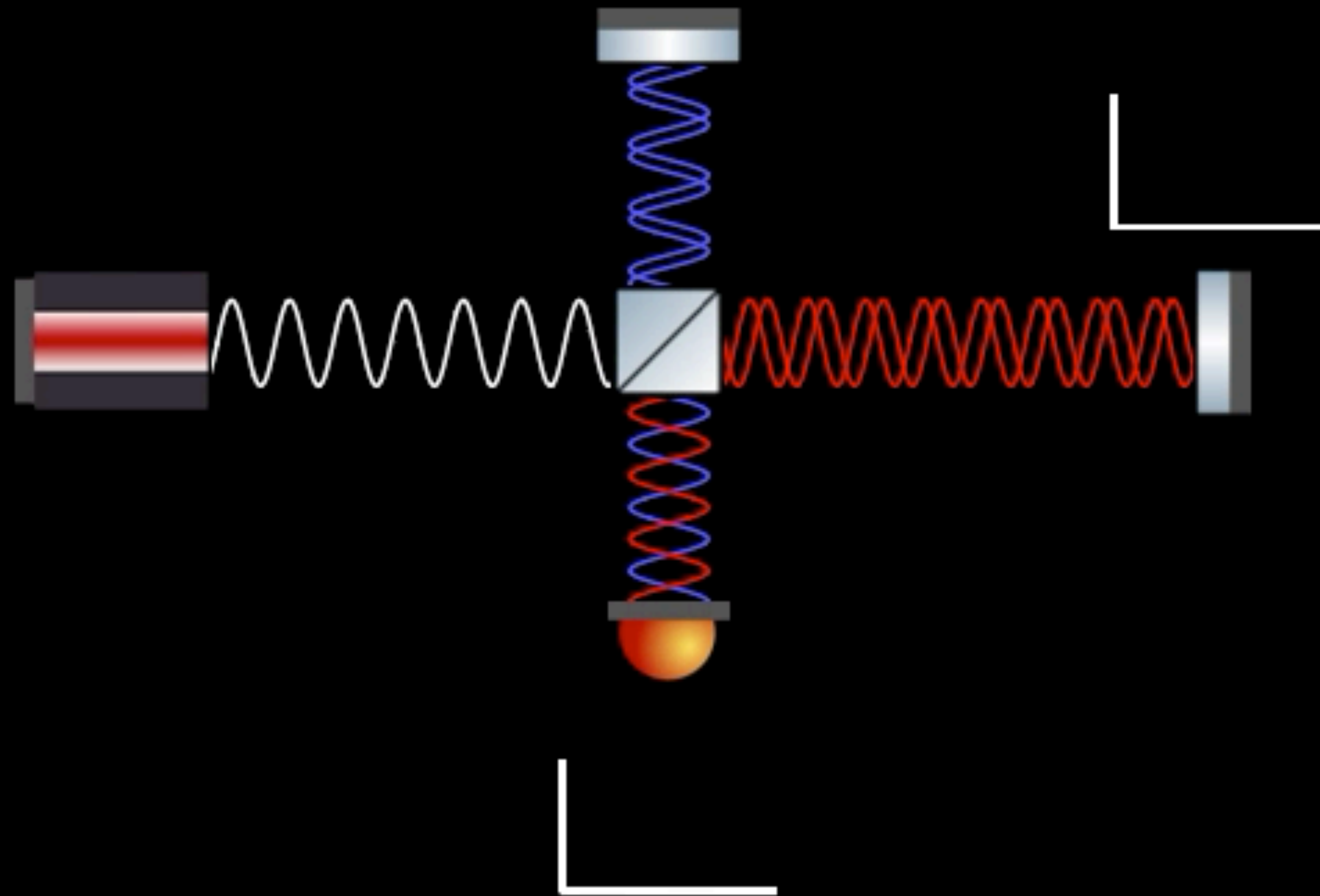




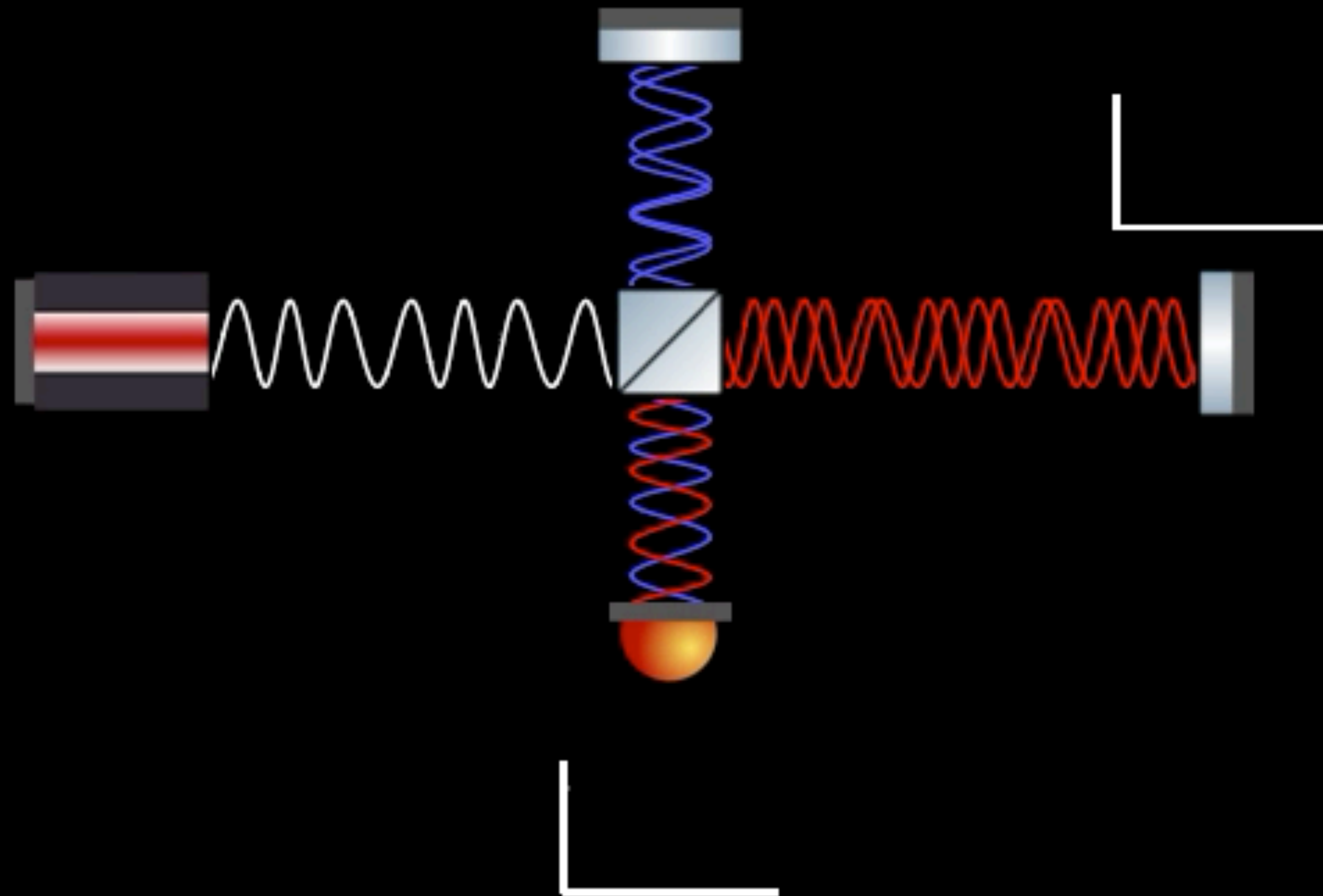
# Laser noise cancellation in interferometers



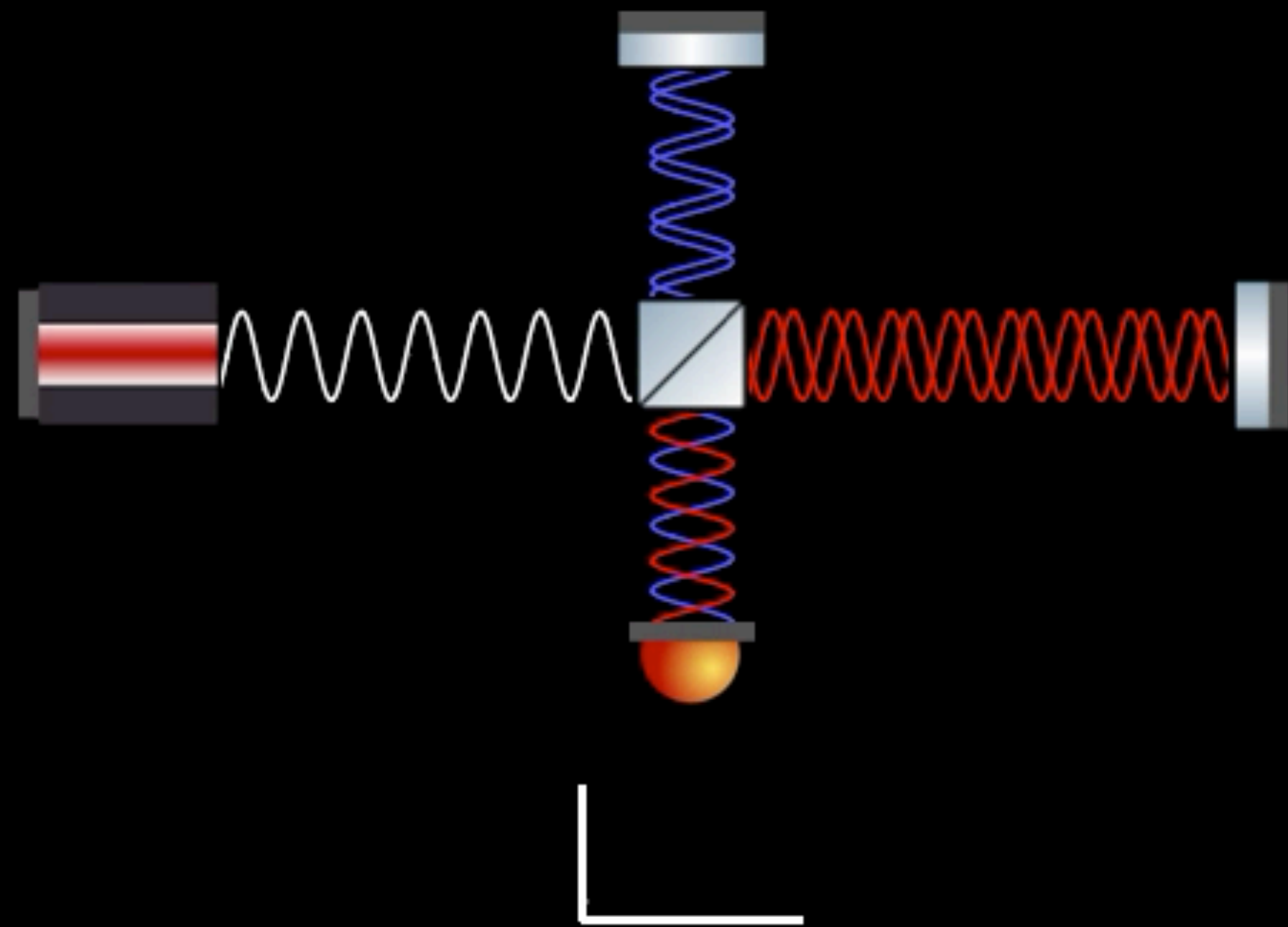
# Laser noise cancellation in interferometers



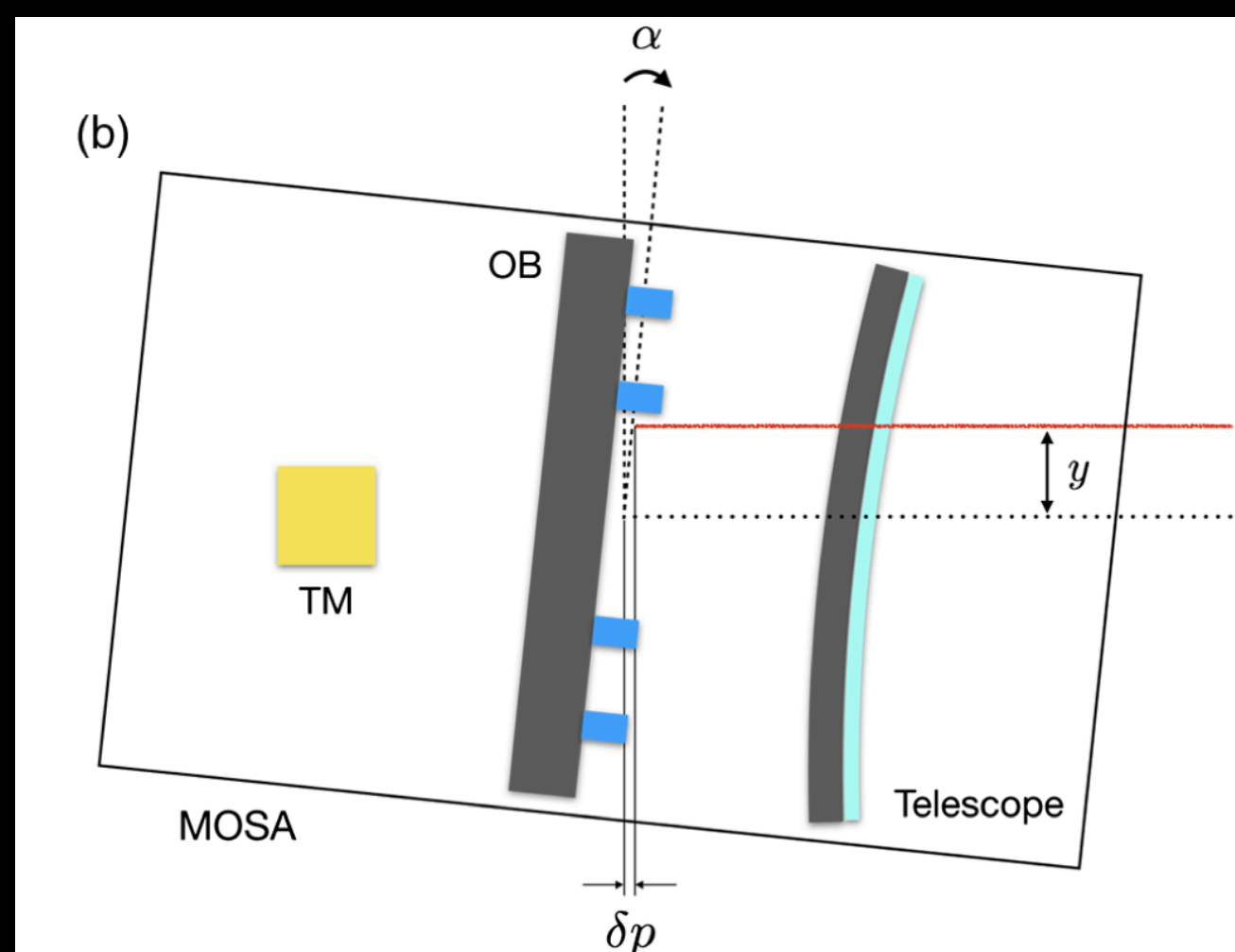
# Laser noise cancellation in interferometers



# Further complications: beyond laser noise suppression



- In LISA: spacecraft are moving
- Interferometric signals are MHz beatnotes
- GW is encoded in phase fluctuations
- To recover the signal, we must compare to a local reference clock.
- Existing clocks not good enough, corrected with dedicated measurements
- Optical system not static, angular jitters couple into main readout
- Resulting Tilt-To-Length (TTL) coupling corrected with dedicated measurement of beam tilts
- In the end: Combine  $\approx 66$  interferometric measurements with ground tracking information and auxiliary sensors to produce 3 synchronized scientific variables

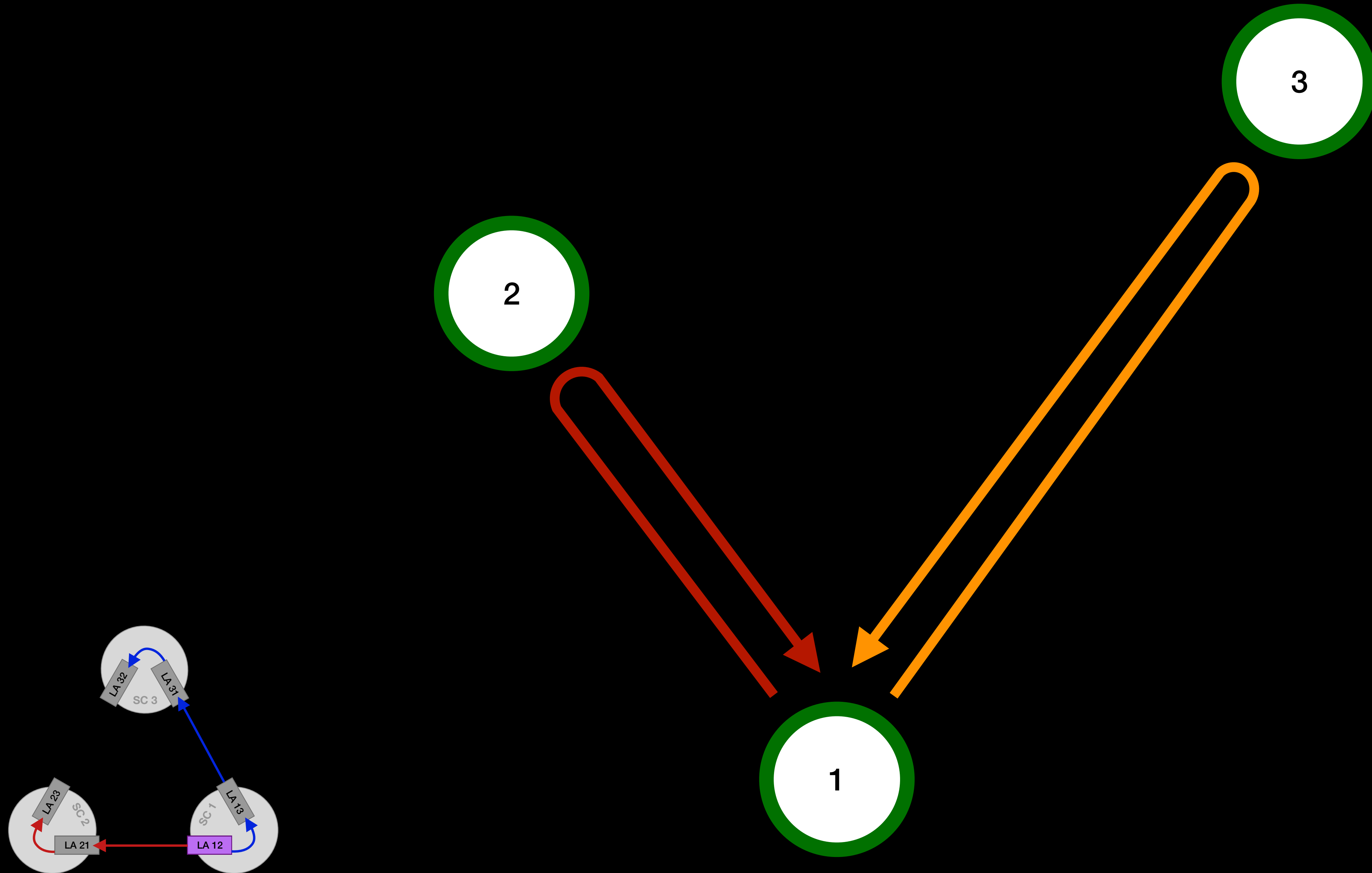


Source: 10.1103/PhysRevD.106.042005

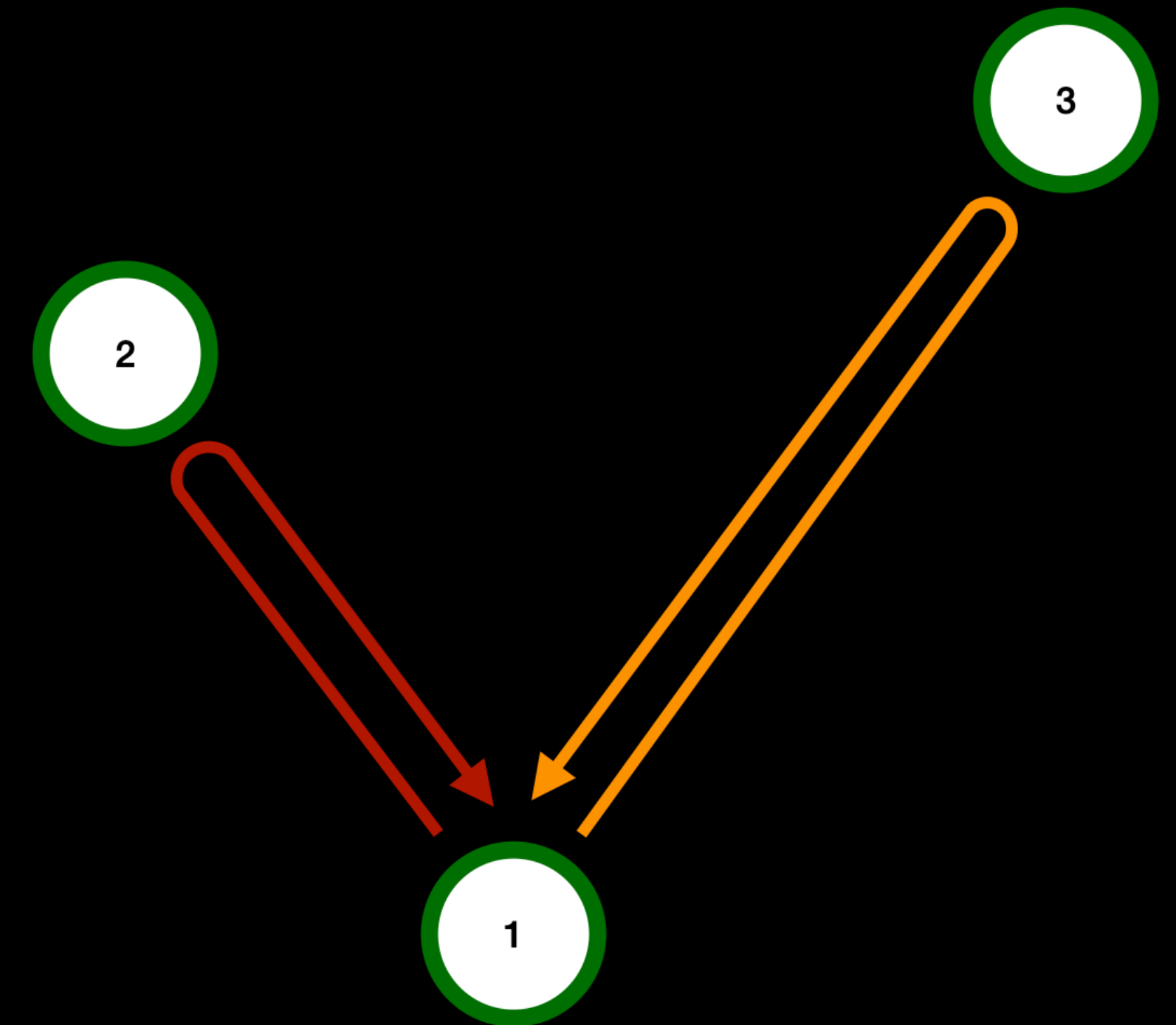
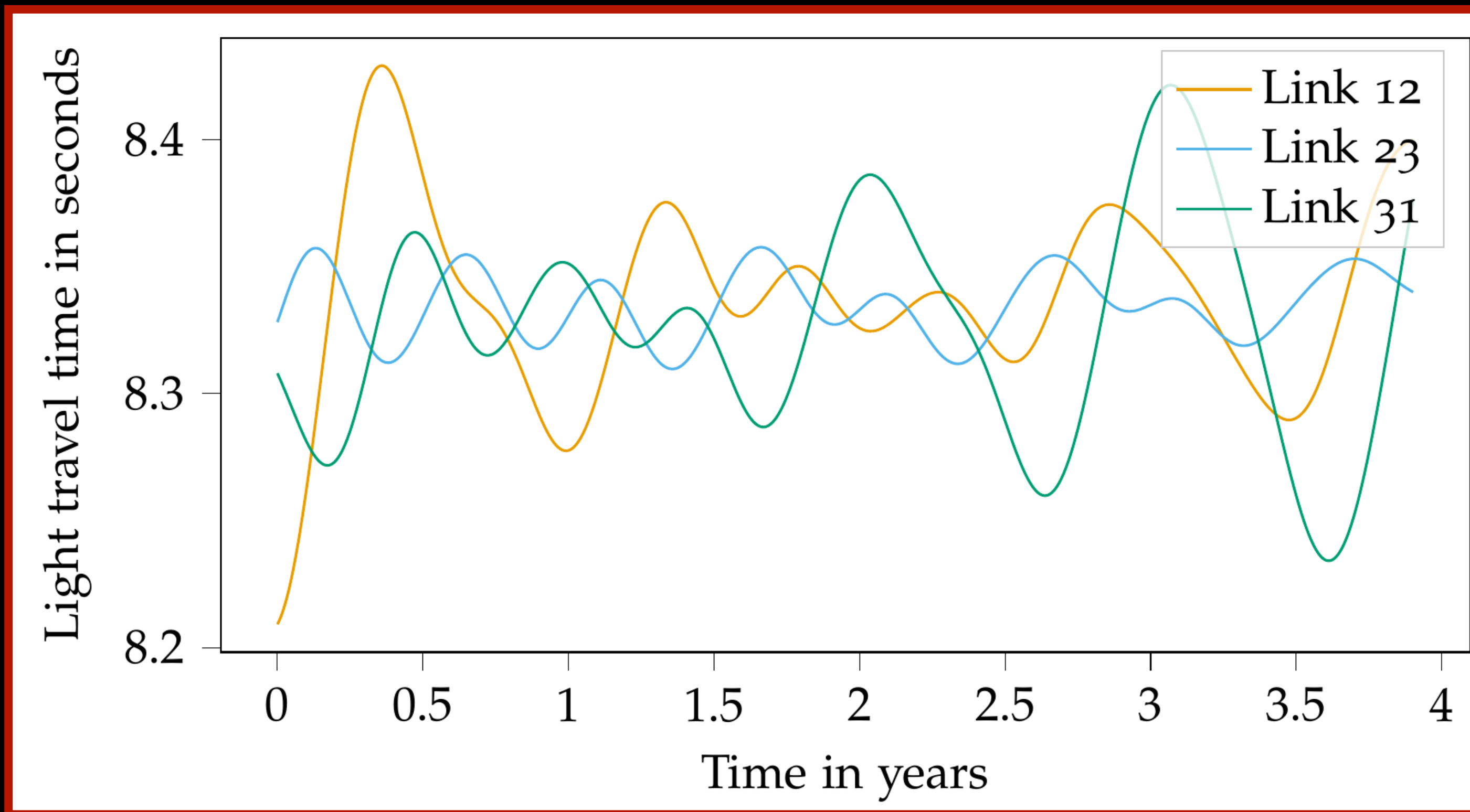
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# Time delay interferometry

# Laser noise cancellation in LISA



# Laser noise cancellation in LISA

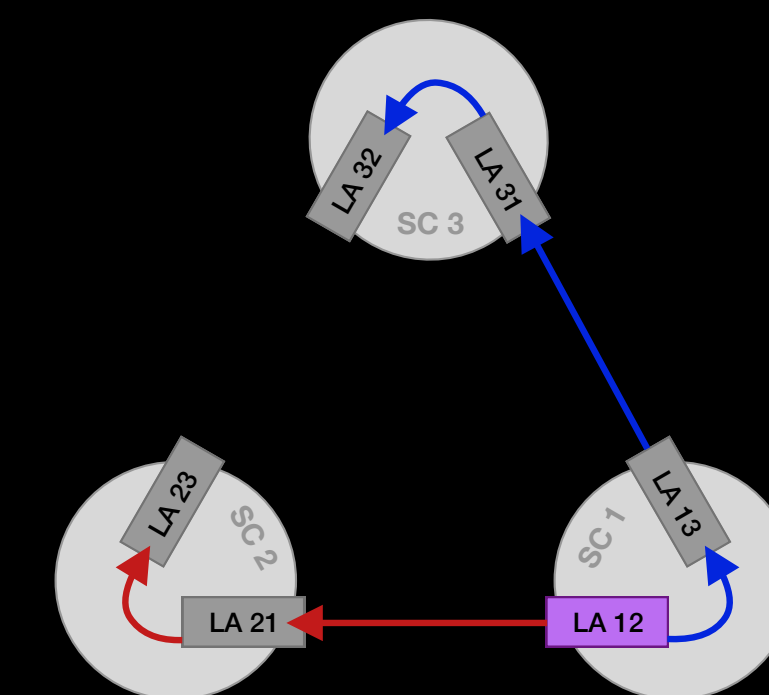
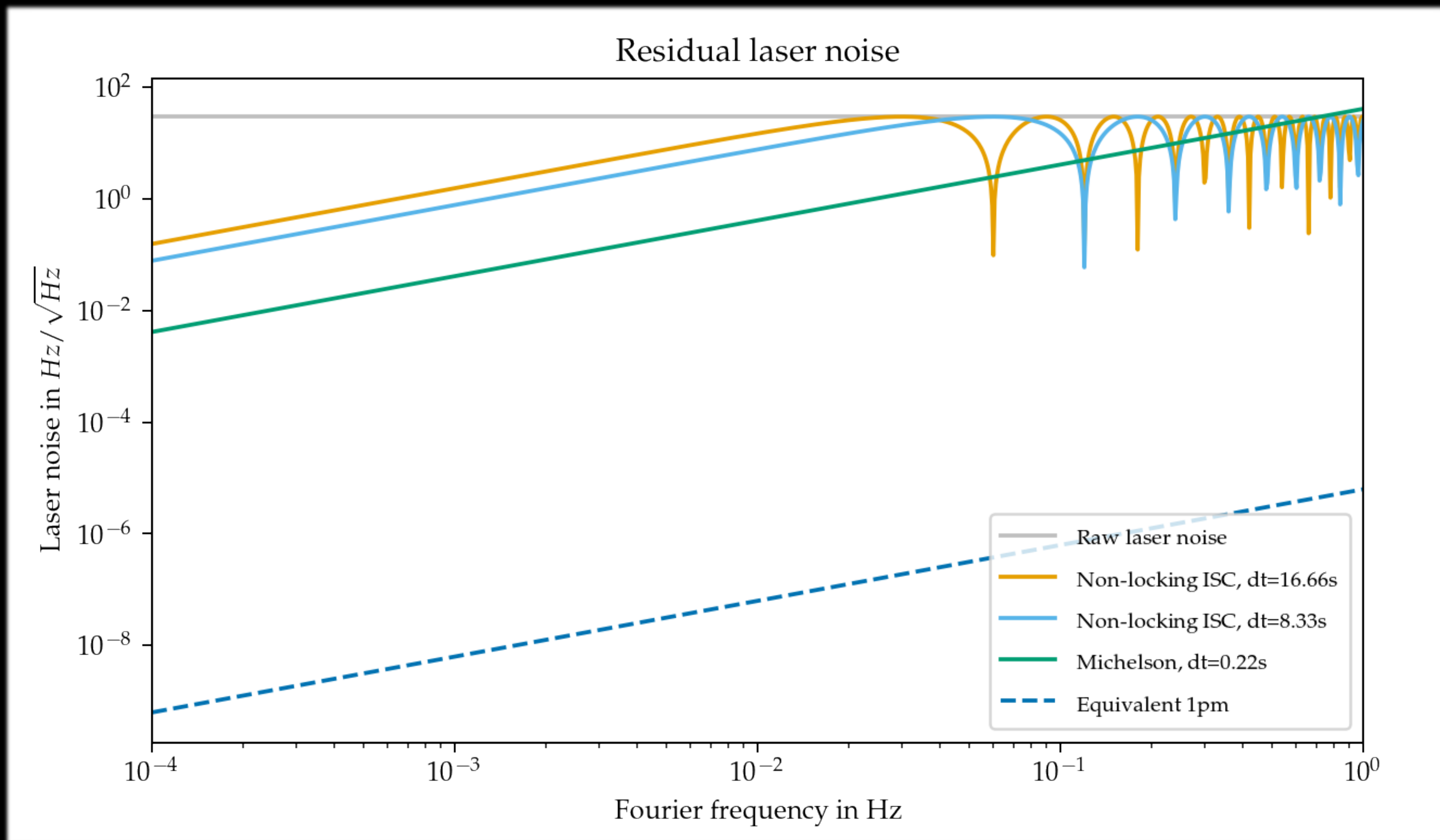


- Laser noise will enter as  $\Phi(t - \delta t_1) - \Phi(t - \delta t_2)$ , which in the frequency domain becomes (with  $\delta t = \delta t_1 - \delta t_2$ )

$$S_{\Phi, \text{TDI}} = 4 \sin(\pi f \delta t)^2 S_{\Phi} \approx (2\pi f)^2 \delta t^2 S_{\Phi}$$

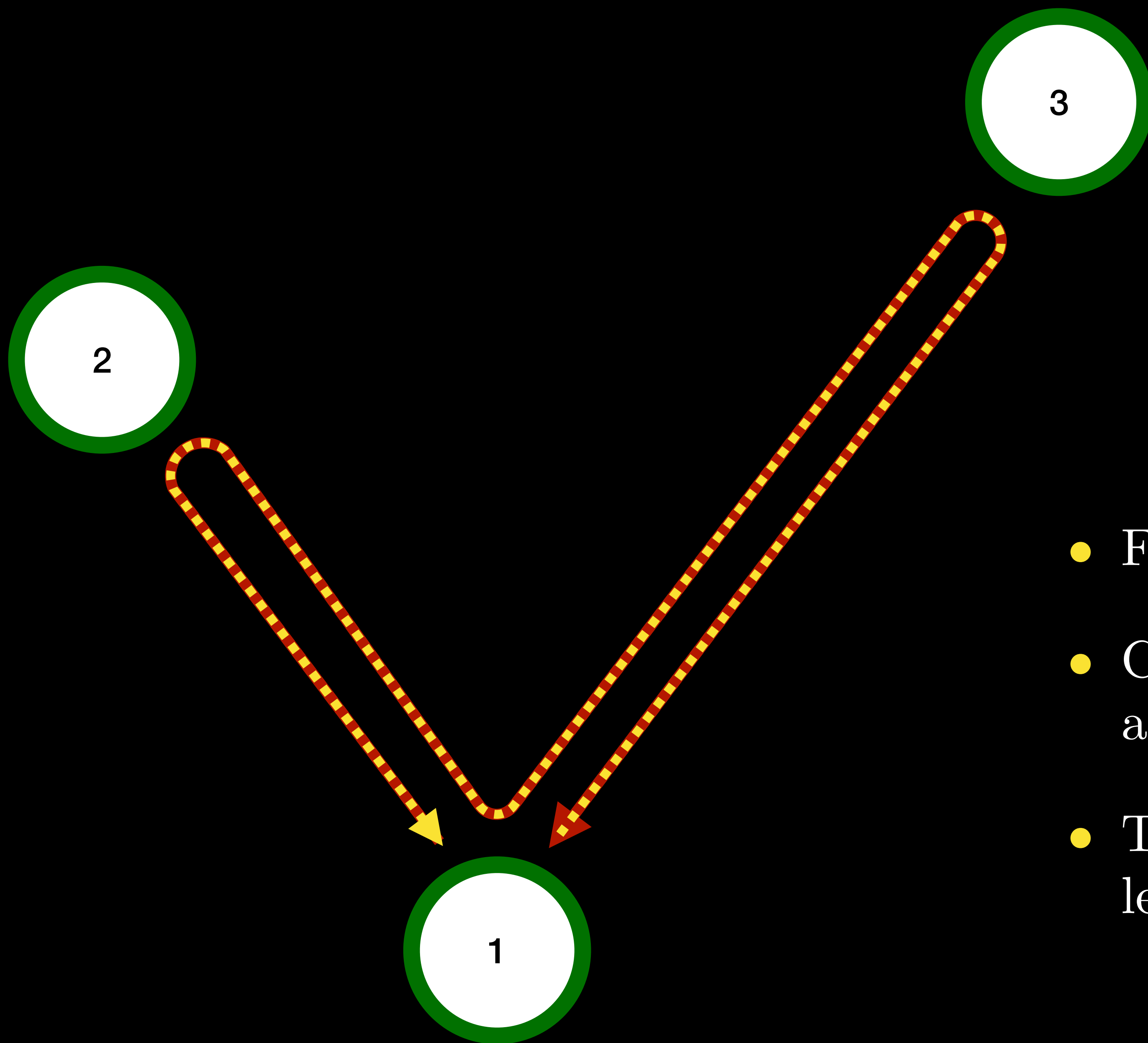
# Residual laser noise in LISA

$$S_{\Phi, \text{TDI}} = 4 \sin(\pi f \delta t)^2 S_{\Phi} \approx (2\pi f)^2 \delta t^2 S_{\Phi}$$





# Time-Delay Interferometry

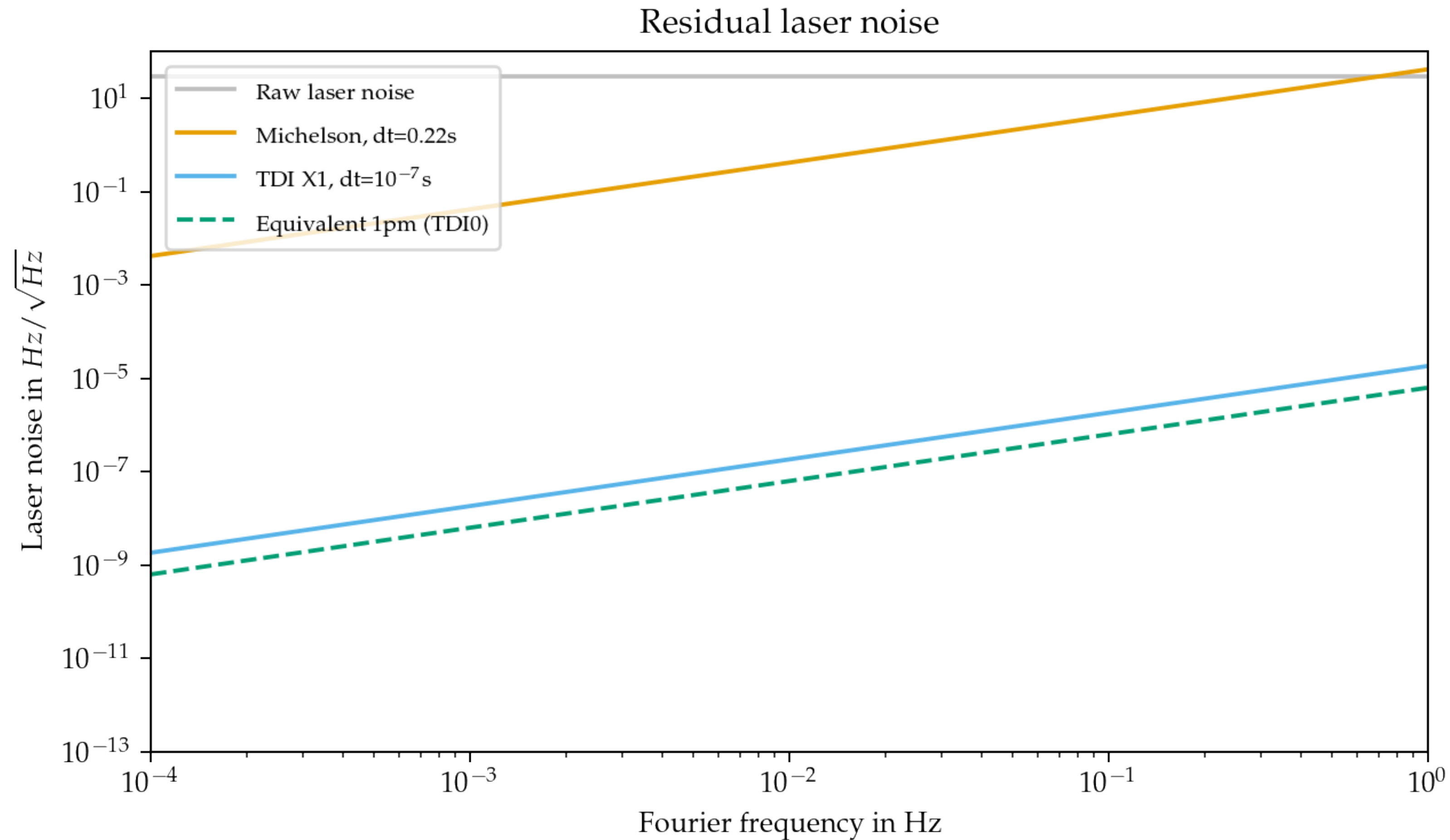


- First proposed in [Tinto et al., 1999]
- Cancel laser noise by constructing equal arm interferometer in post-processing
- This is an example for constant arm lengths (1st generation TDI)

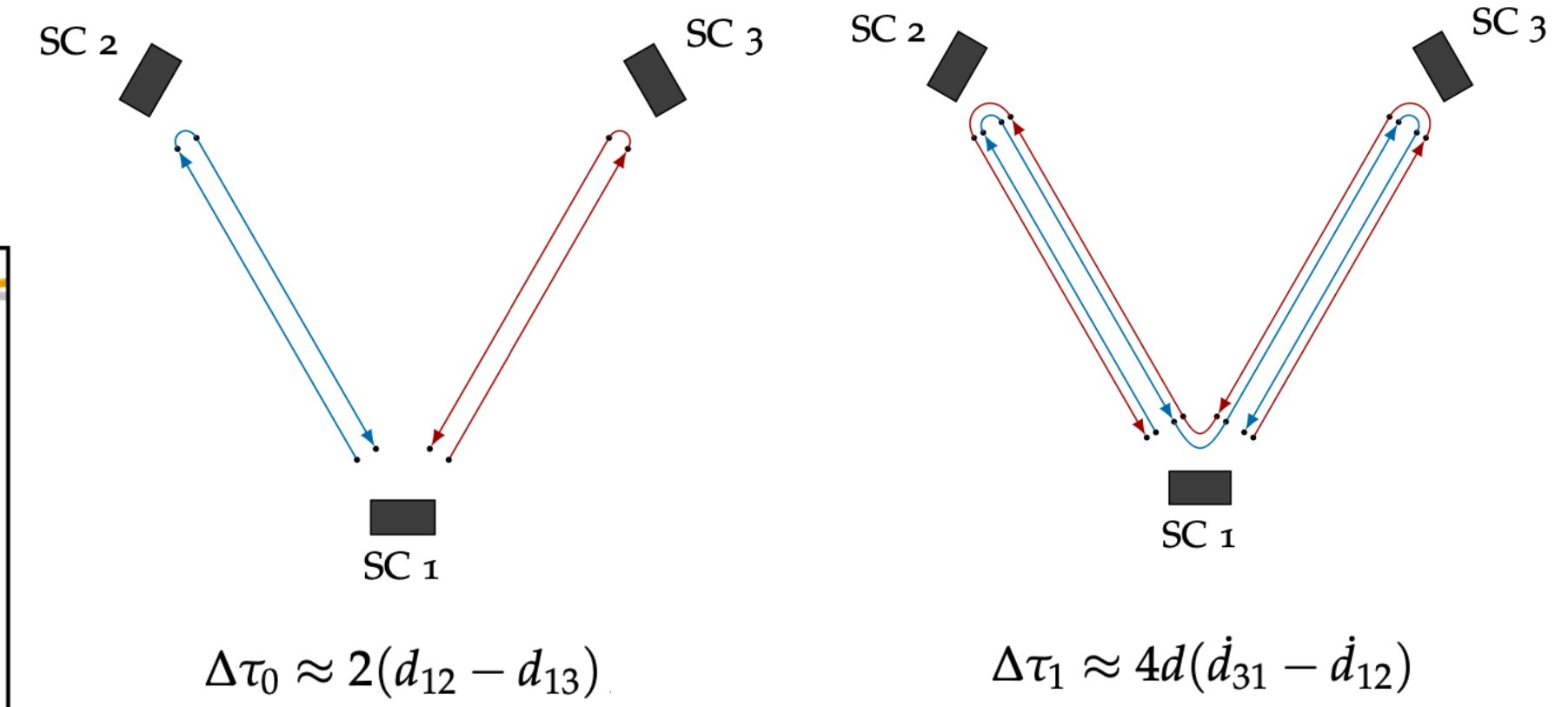
See living review [Tinto & Dhurandhar, 2020] for detailed references on TDI  
First reference in history section (not quite TDI): [Faller and Bender, 1984]

# Residual laser noise in LISA

$$S_{\Phi, \text{TDI}} \approx (2\pi f)^2 \delta t^2 S_{\Phi}$$

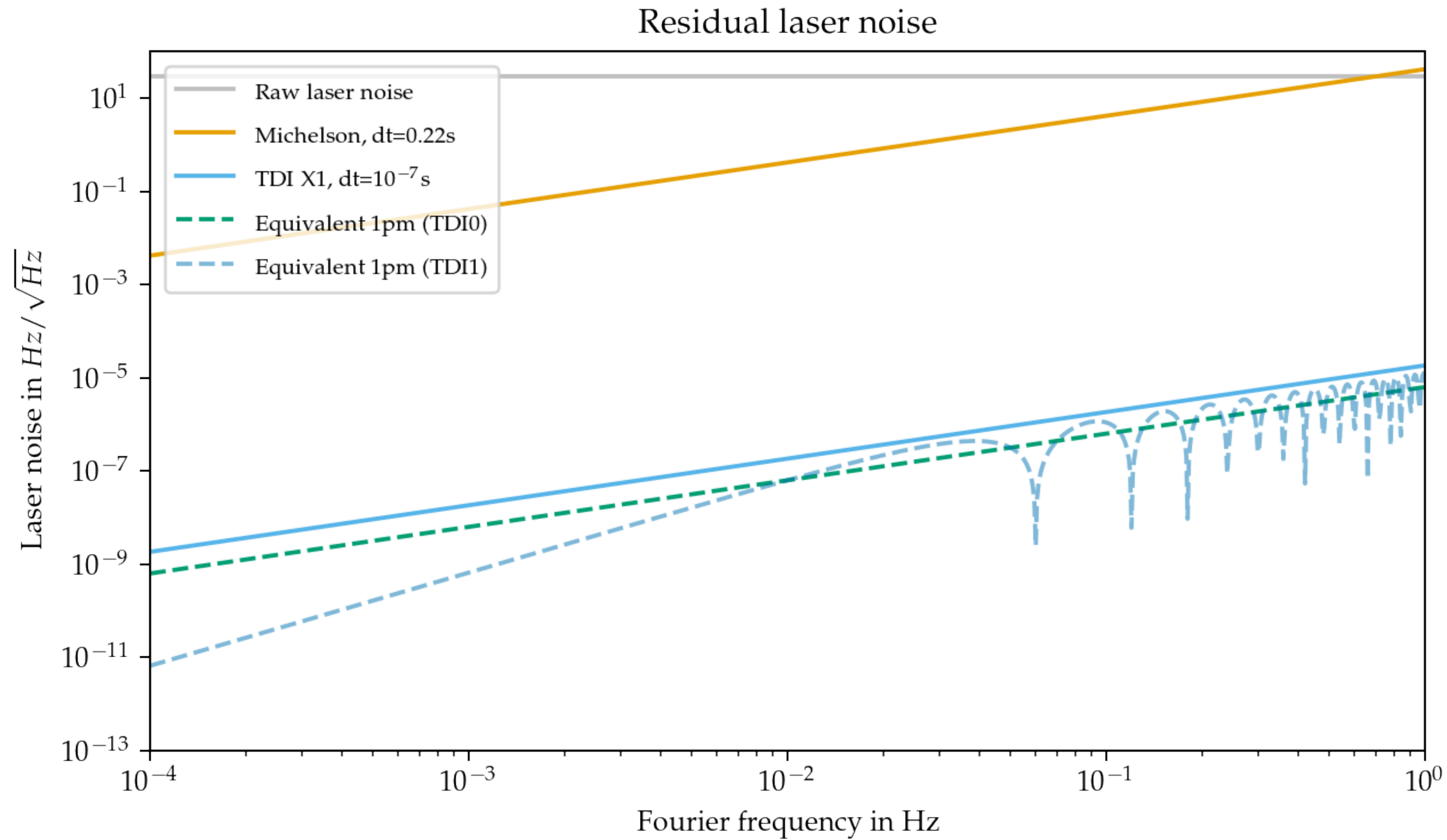


Average light travel times with ESA orbits:  $d_A \approx 8.3\text{s}$ ,  $\dot{d}_A \approx 10^{-9}$  and  $\ddot{d}_A \approx 10^{-15}\text{s}^{-1}$

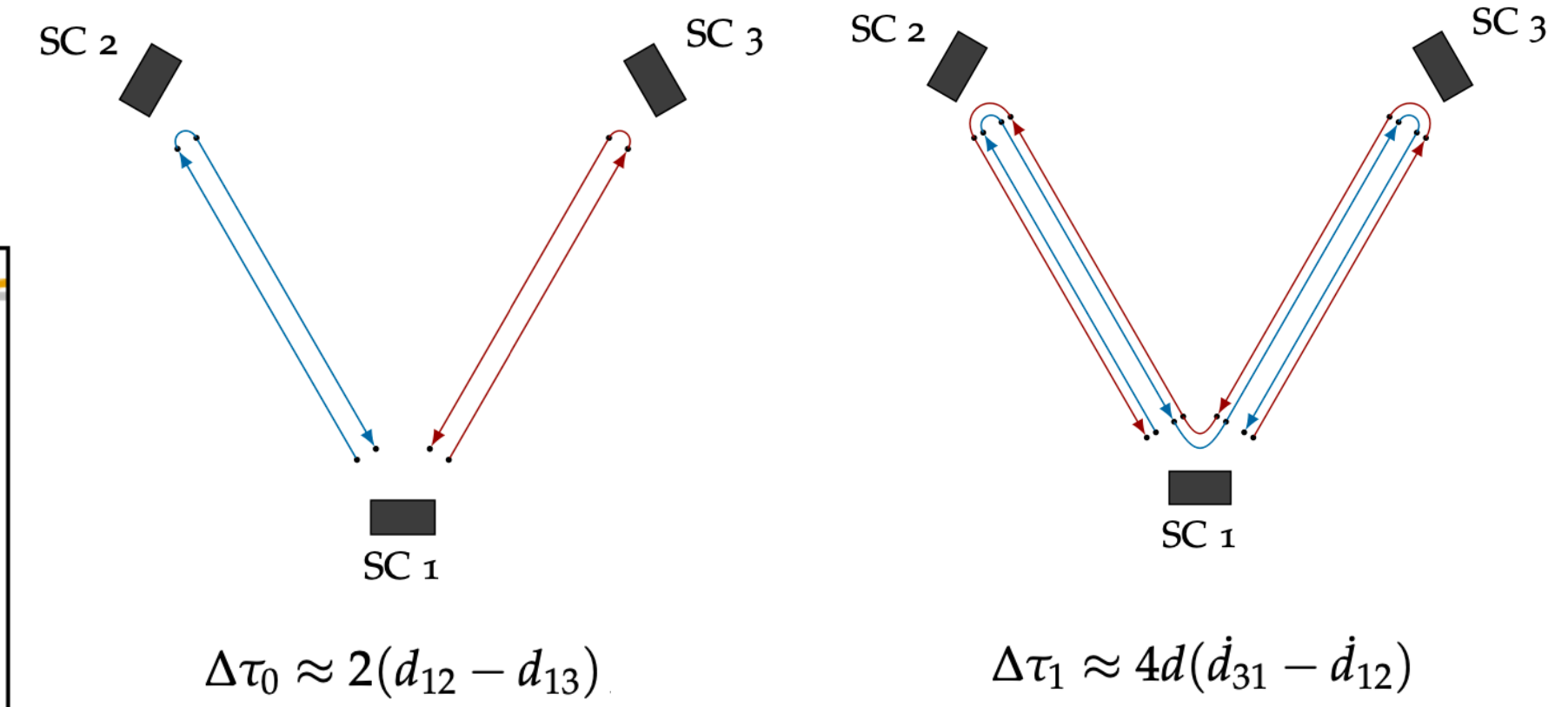


# Residual laser noise in LISA

$$S_{\Phi, \text{TDI}} \approx (2\pi f)^2 \delta t^2 S_{\Phi}$$



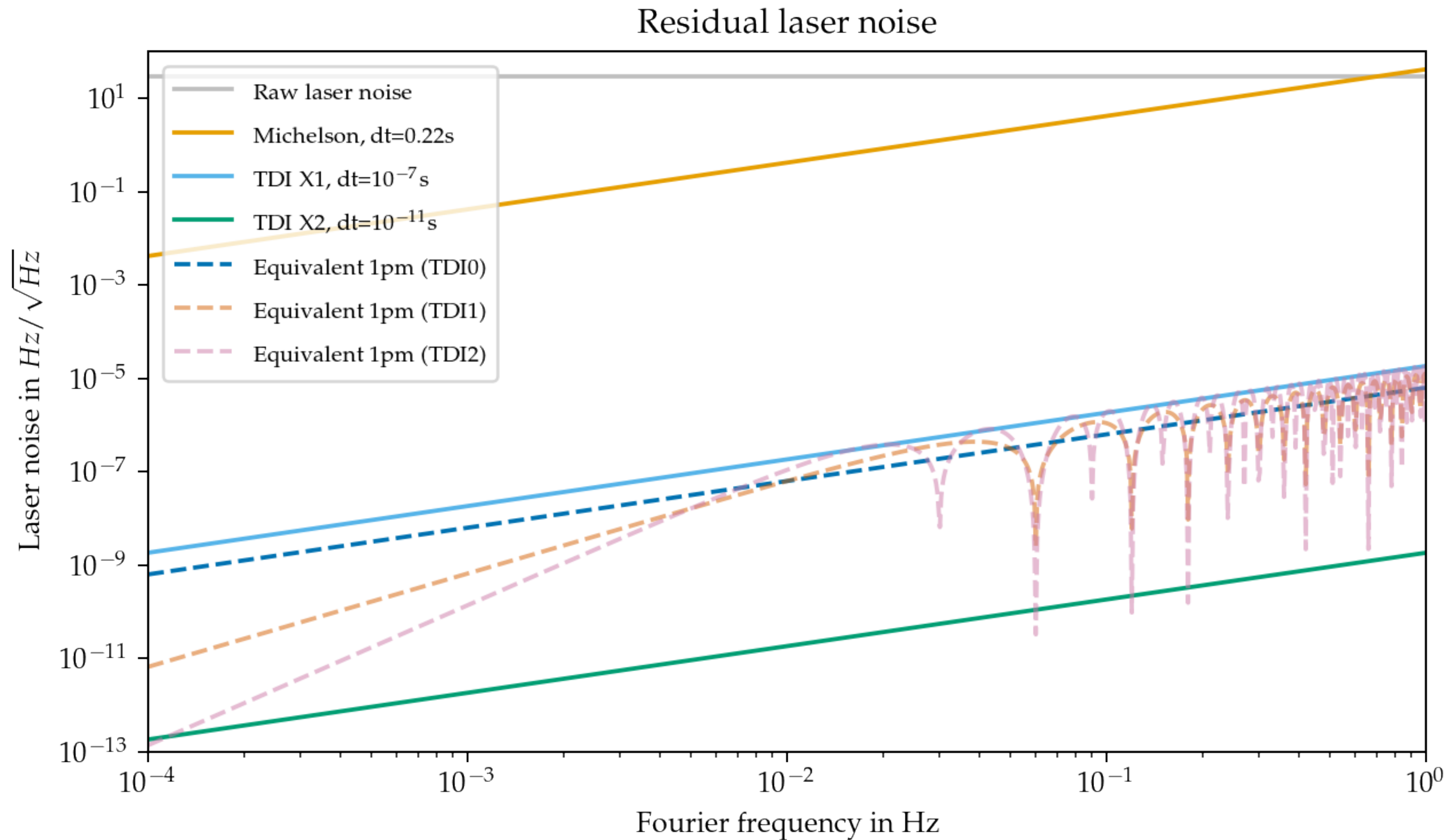
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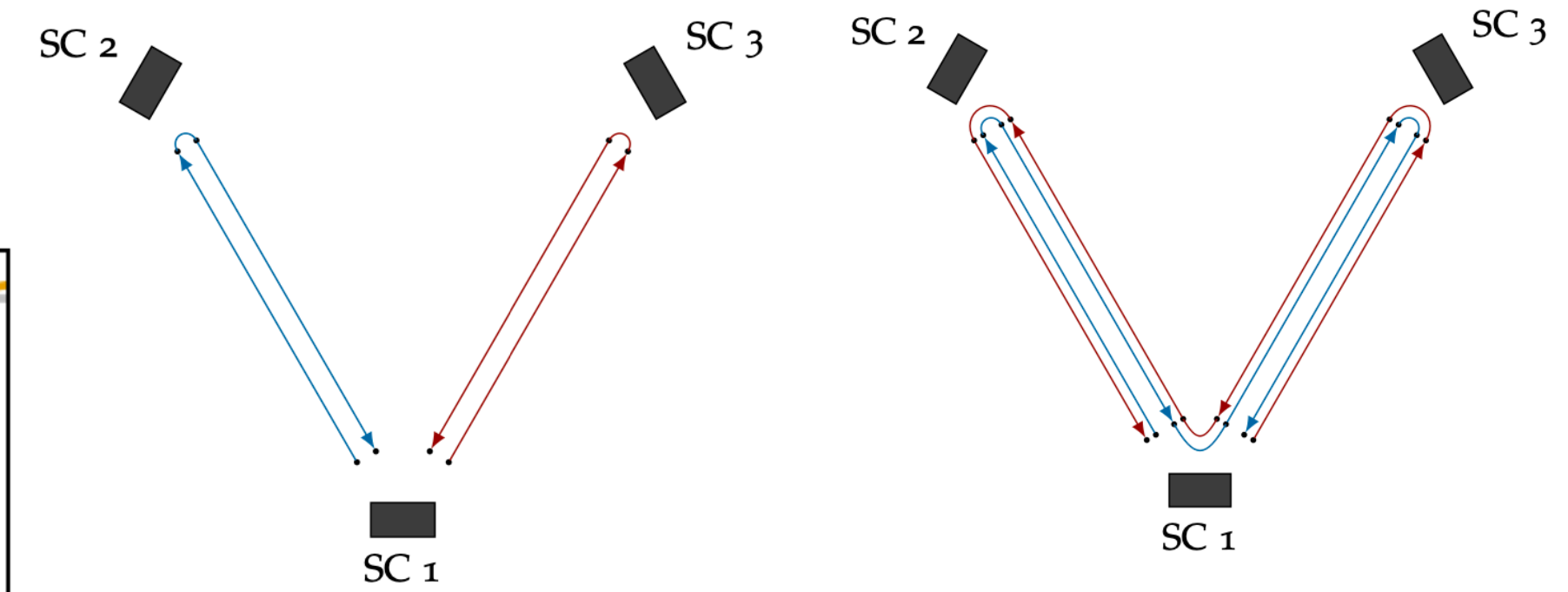
Note: Illustrative, neither laser noise nor actual requirement are white across the band

# Residual laser noise in LISA

$$S_{\Phi, \text{TDI}} \approx (2\pi f)^2 \delta t^2 S_{\Phi}$$

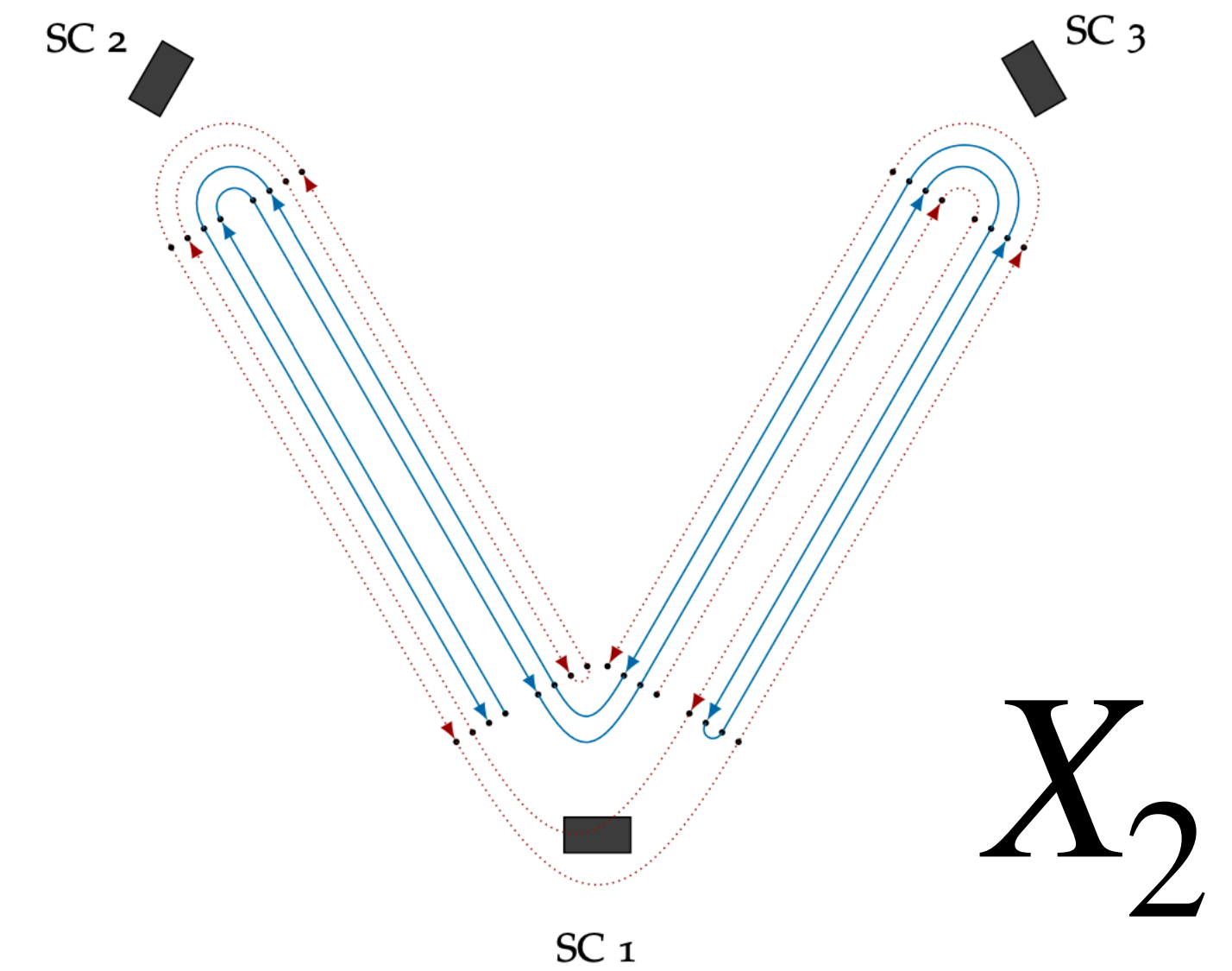


Average light travel times with ESA orbits:  $d_A \approx 8.3 \text{ s}$ ,  $\dot{d}_A \approx 10^{-9}$  and  $\ddot{d}_A \approx 10^{-15} \text{ s}^{-1}$



$$\Delta\tau_0 \approx 2(d_{12} - d_{13})$$

$$\Delta\tau_1 \approx 4d(\dot{d}_{31} - \dot{d}_{12})$$



$$\Delta\tau_2 \approx 8d[(\dot{d}_{12}^2 - \dot{d}_{31}^2) - 2d(\ddot{d}_{12} - \ddot{d}_{31})]$$

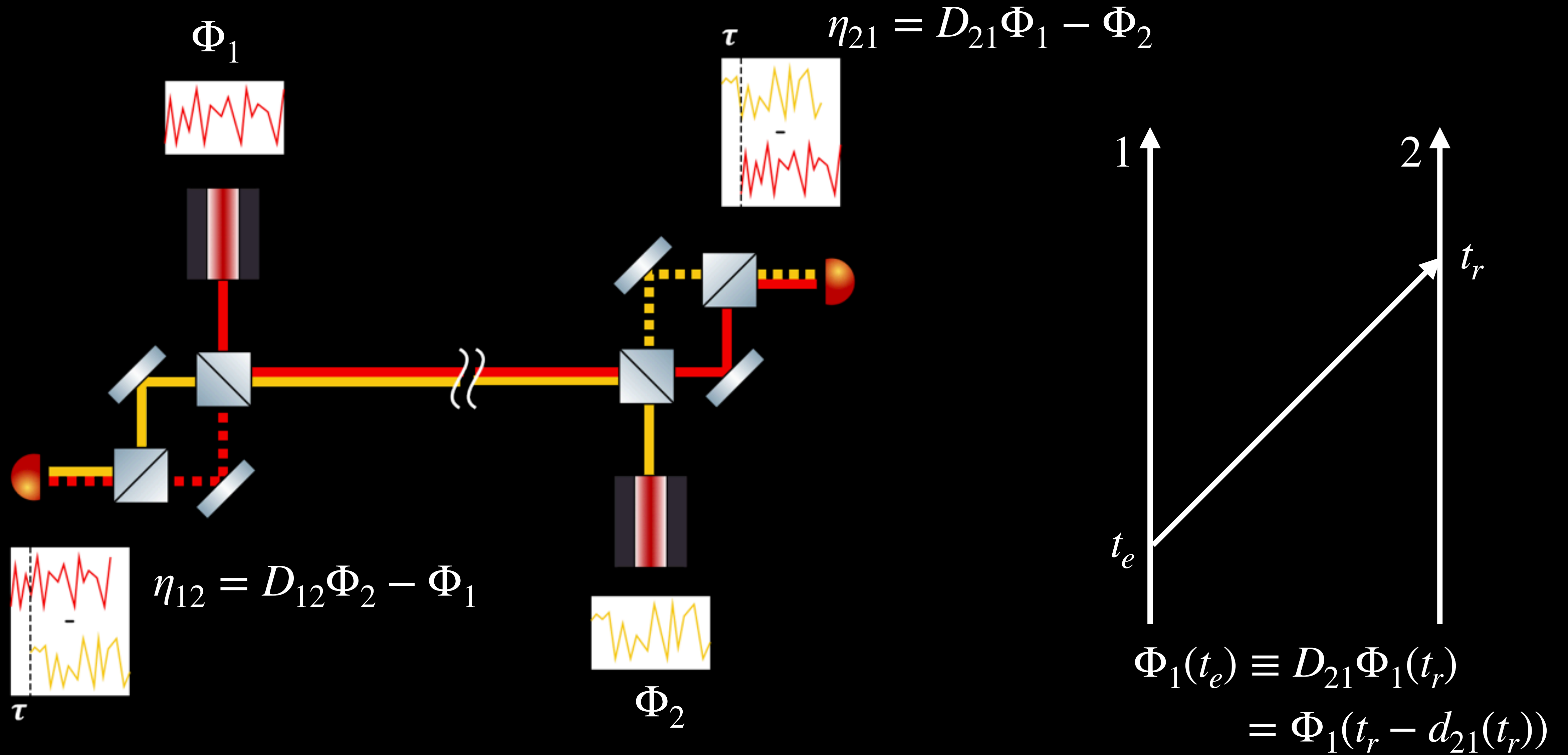
**X<sub>2</sub>**

Note: Illustrative, neither laser noise nor actual requirement are white across the band

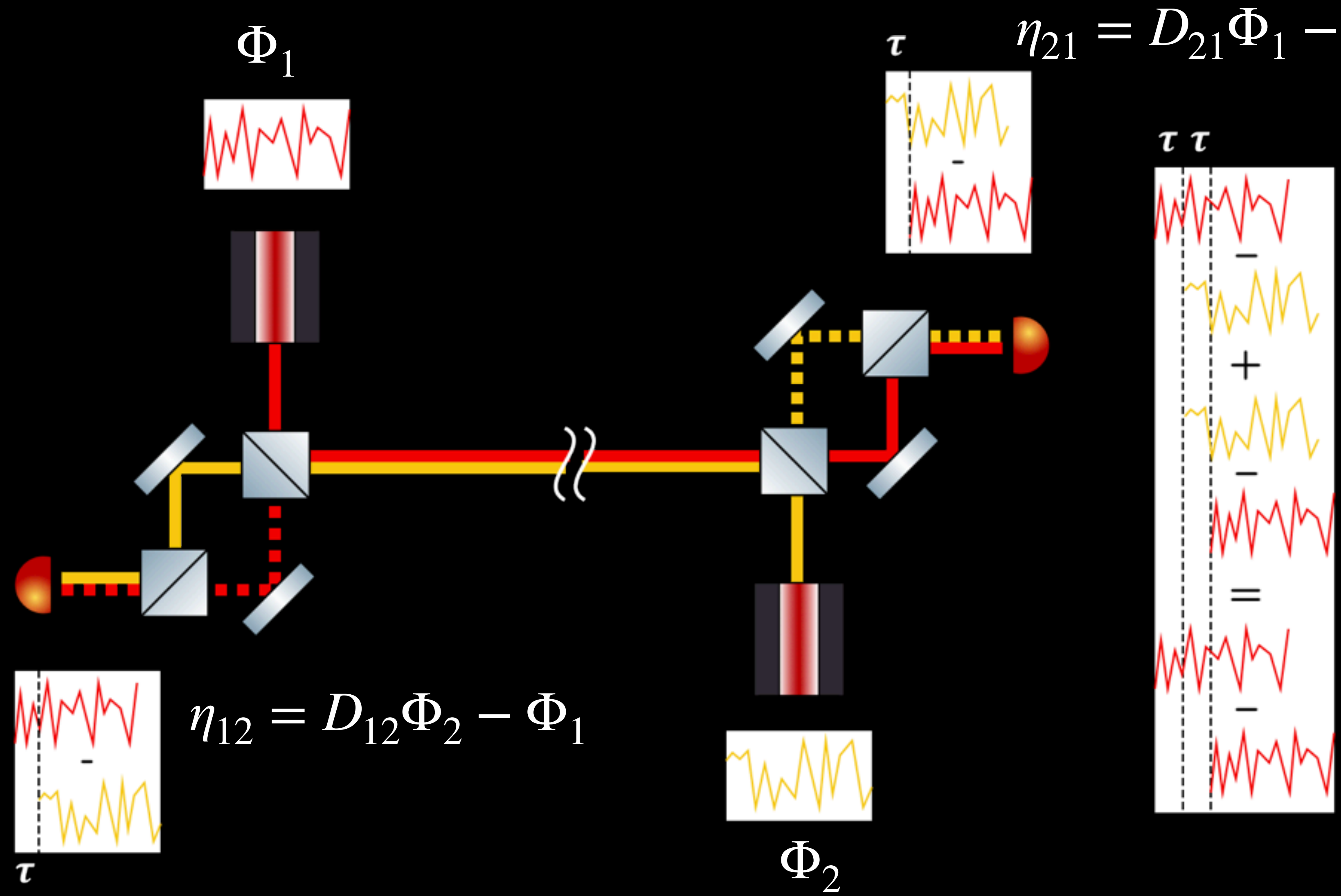
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How does TDI work, in practice?

# TDI toy model

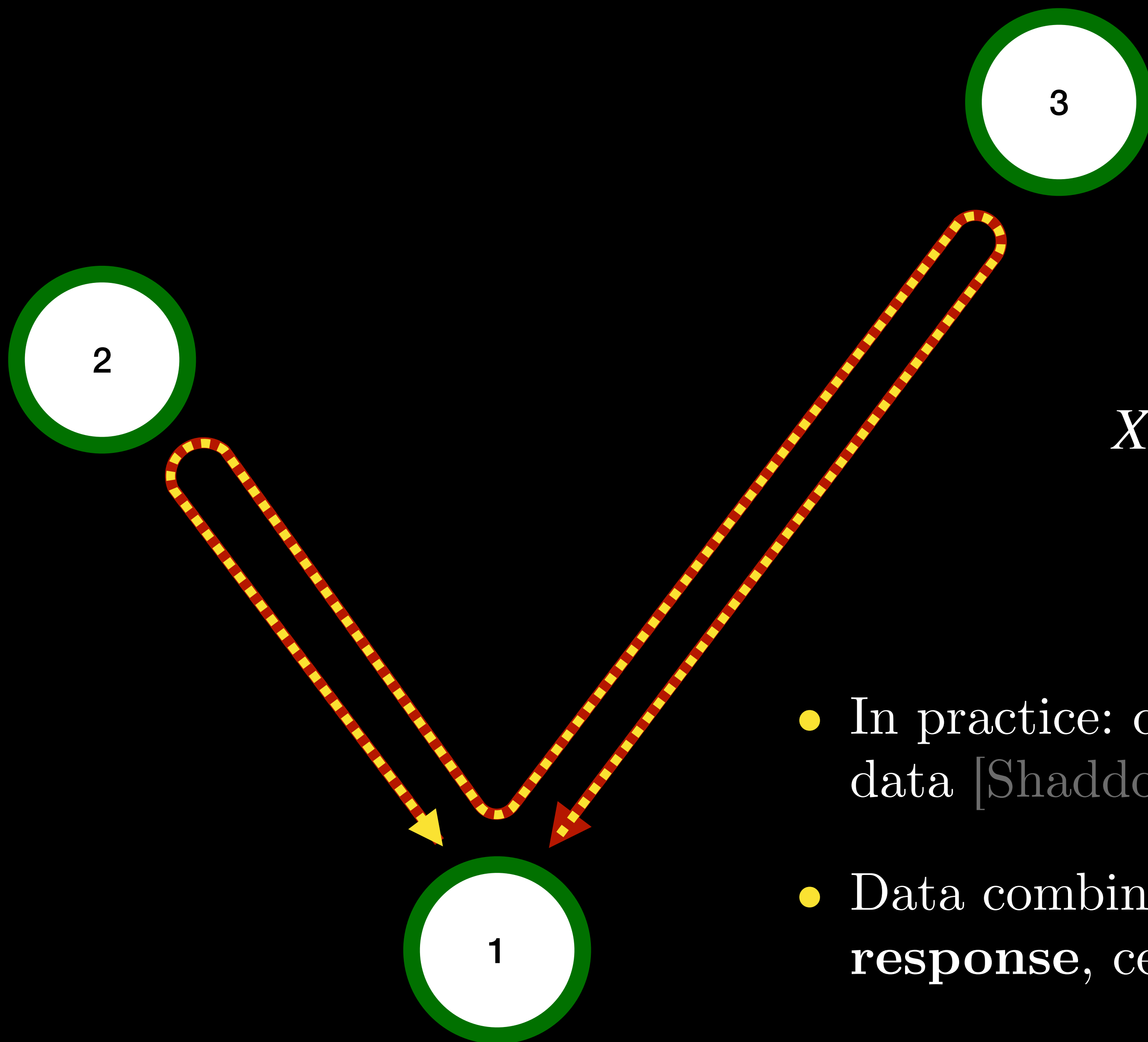


# TDI toy model



$$\begin{aligned}
 TDI &= \eta_{12} + \mathbf{D}_{12}\eta_{21} \\
 &= \mathbf{D}_{12}\Phi_2 - \Phi_1 \\
 &\quad + \mathbf{D}_{12}(\mathbf{D}_{21}\Phi_1 - \Phi_2) \\
 &= \mathbf{D}_{121}\Phi_1 - \Phi_1
 \end{aligned}$$

# Full first generation TDI



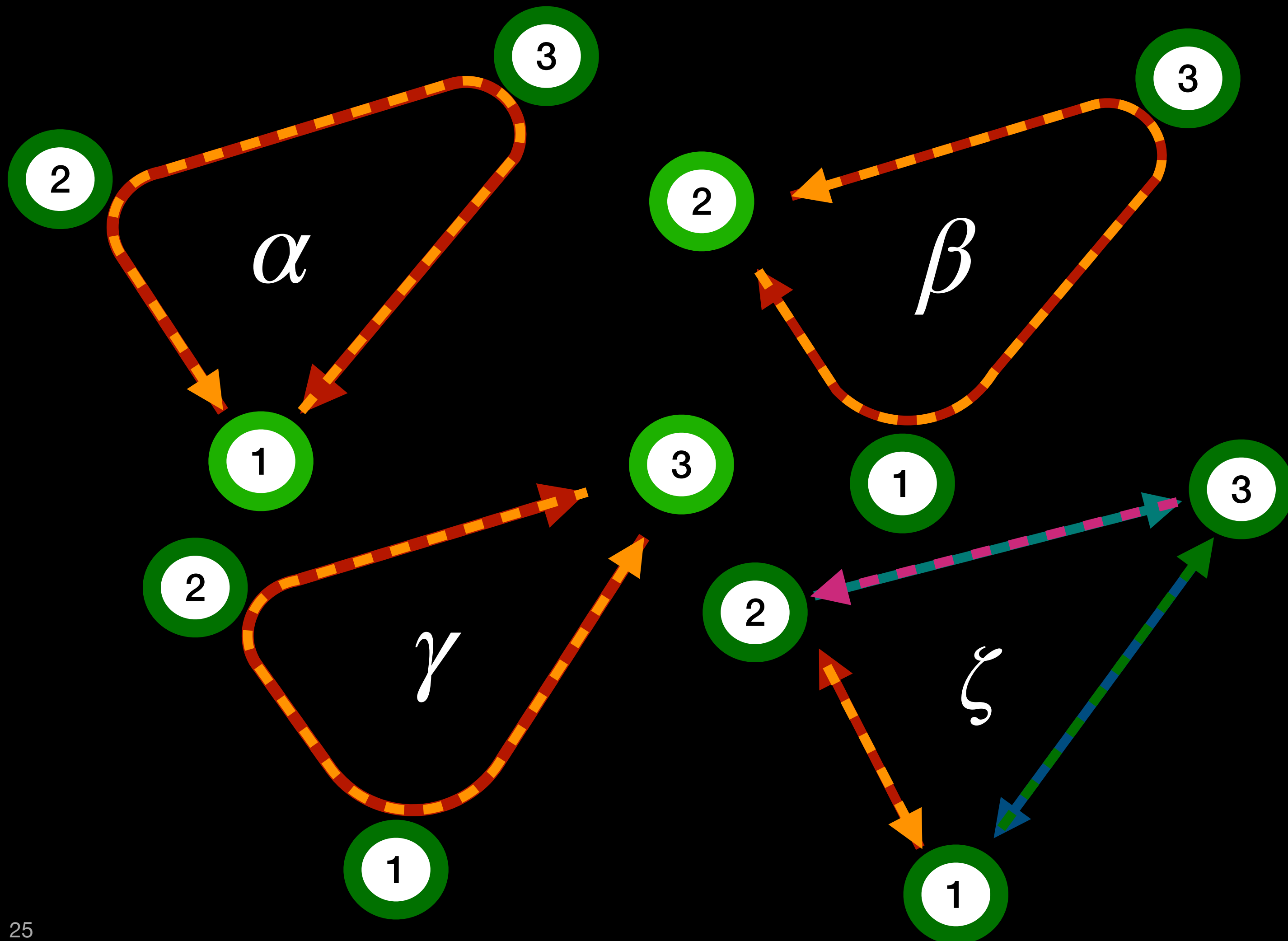
$$\begin{aligned} X &= \eta_{12} + D_{12}\eta_{21} + D_{121}\eta_{13} + D_{1213}\eta_{31} \\ &\quad - \eta_{12} - D_{13}\eta_{31} - D_{131}\eta_{13} - D_{1312}\eta_{21} \\ &= (D_{12131} - D_{13121})\Phi_1 \end{aligned}$$

- In practice: delays realised by interpolating 4 Hz data [Shaddock et al., 2004].
- Data combination has **strong impacts on GW response**, central to LISA data analysis



# Which variables to use?

- For a static constellation, all TDI variables can be built from 4 generators [Dhurandhar et al., 2002]
- Only three independent:  $(1 - D_{12}D_{23}D_{31})\zeta = (D_{23} - D_{31}D_{12})\alpha + (D_{31} - D_{12}D_{23})\beta + (D_{12} - D_{23}D_{31})\gamma$

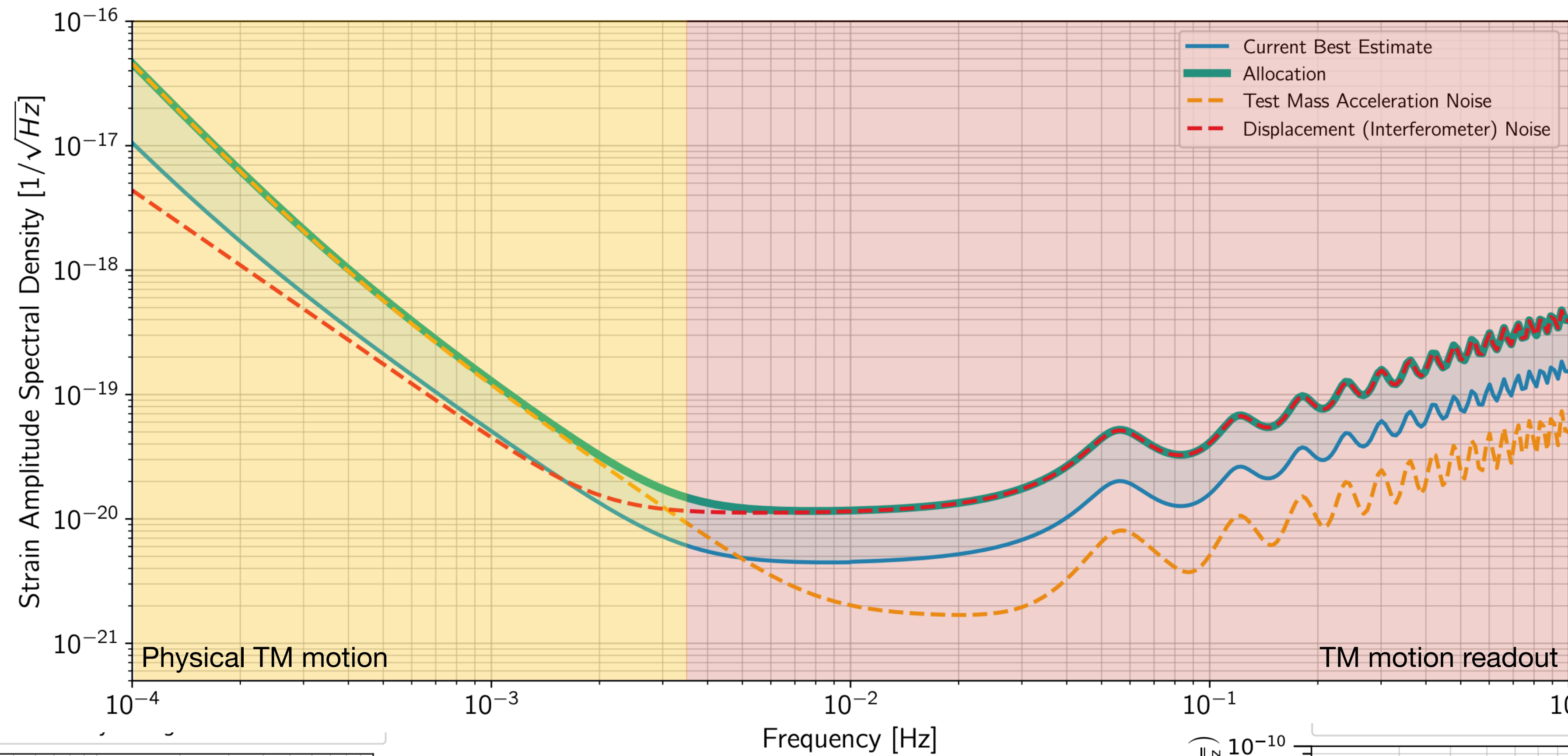


- In ‘good’ (?) approximation:
  - Only 3 channels independent even in realistic scenarios (time-varying orbits)
  - Popular choice: 3 Michelson combinations ( $X_2, Y_2, Z_2$ )
  - Under (strong) assumptions: easy to construct noise- and signal orthogonal (A, E, T)
  - At low frequency: only A, E sensitive to GWs, and  $S_h^A \simeq S_h^E \simeq S_h^X$

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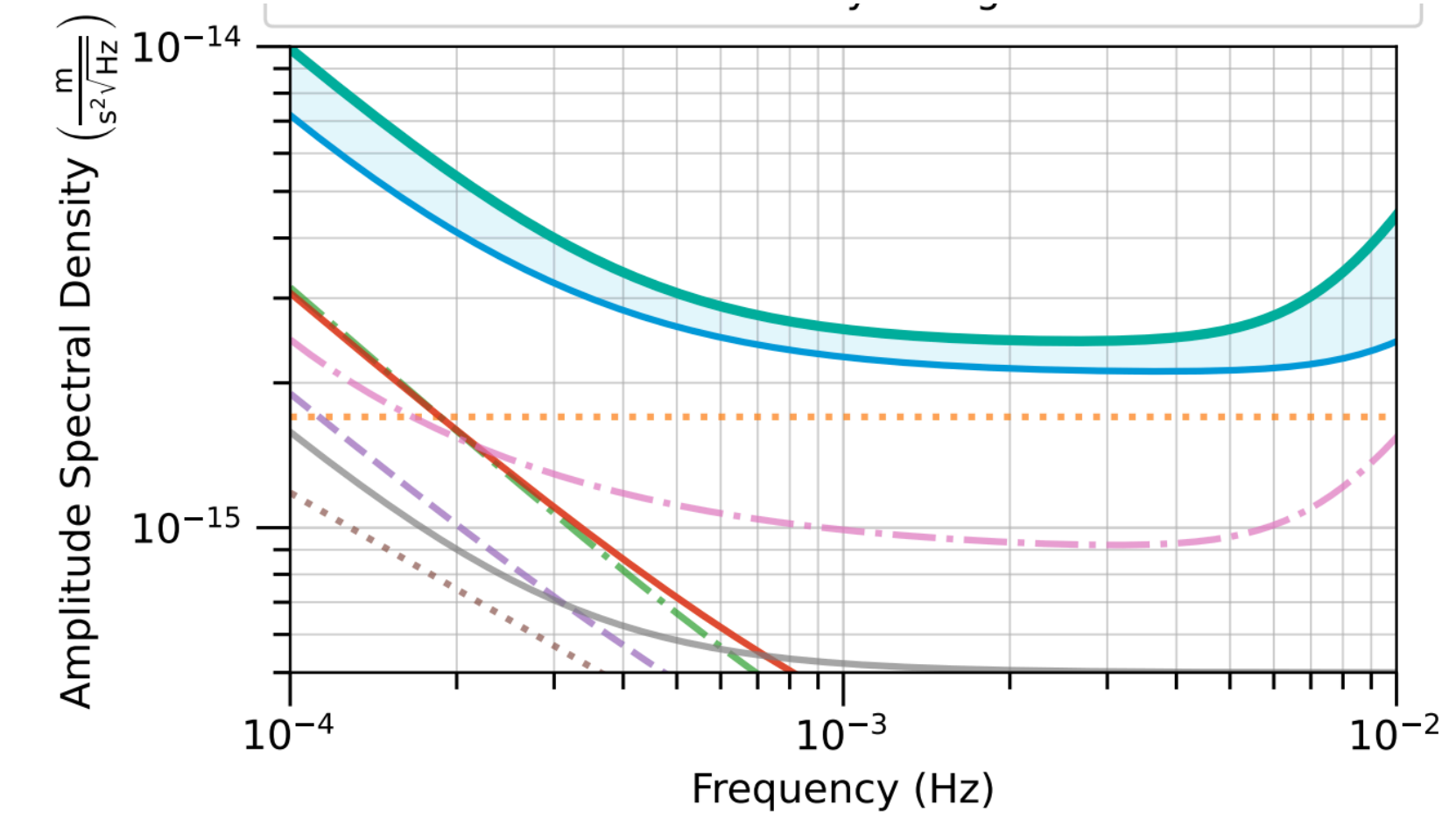
# LISA Performance and Sensitivity

# Main limiting noise sources left after TDI



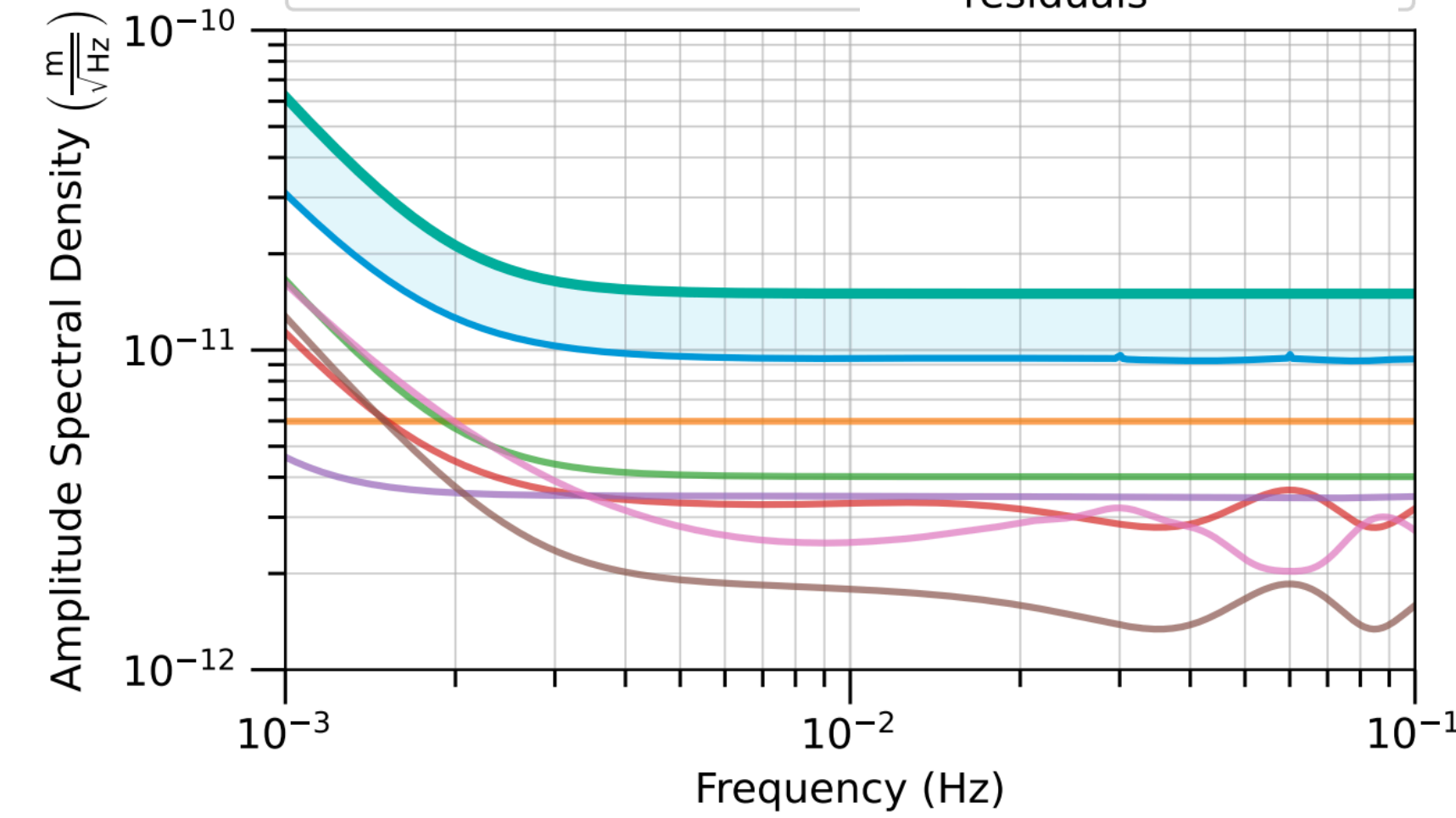
- allocation
- current best estimate
- actuation noise
- brownian noise
- GRS-OB baseline stability
- $\Phi$  actuation noise
- stray voltage noise
- interplanetary B-field
- S/C-MOSA coupling
- gravitational

- allocation
- current best estimate
- Science Interferometer shot noise
- Science Interferometer readout noise
- local interferometry
- TTL residuals
- Thermo-mechanical Noise
- Post-processing residuals

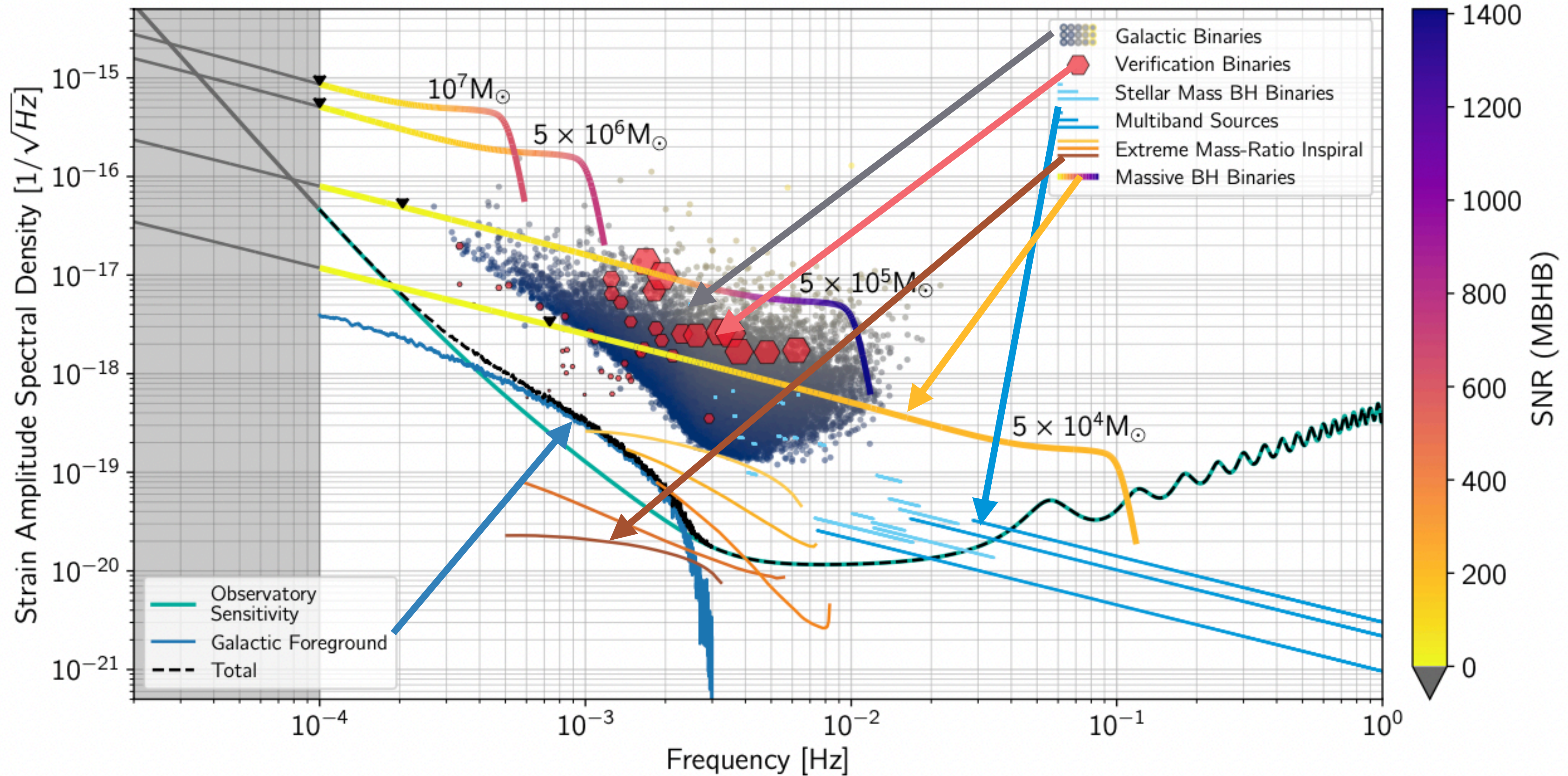


$$S_h(f) \approx \frac{T_{acc}^X S_{acc}^X + T_{oms}^X S_{oms}^X}{2 R_{GW}^X}$$

!!!



# LISA Sensitivity vs. science objectives



# LISA Sensitivity vs. science objectives

**SO1:** Study the formation and evolution of compact binary stars and the structure of the Milky Way Galaxy

**SO2:** Trace the origins, growth and merger histories of massive Black Holes

**SO3:** Probe the properties and immediate environments of Black Holes in the local Universe using EMRIs and IMRIs

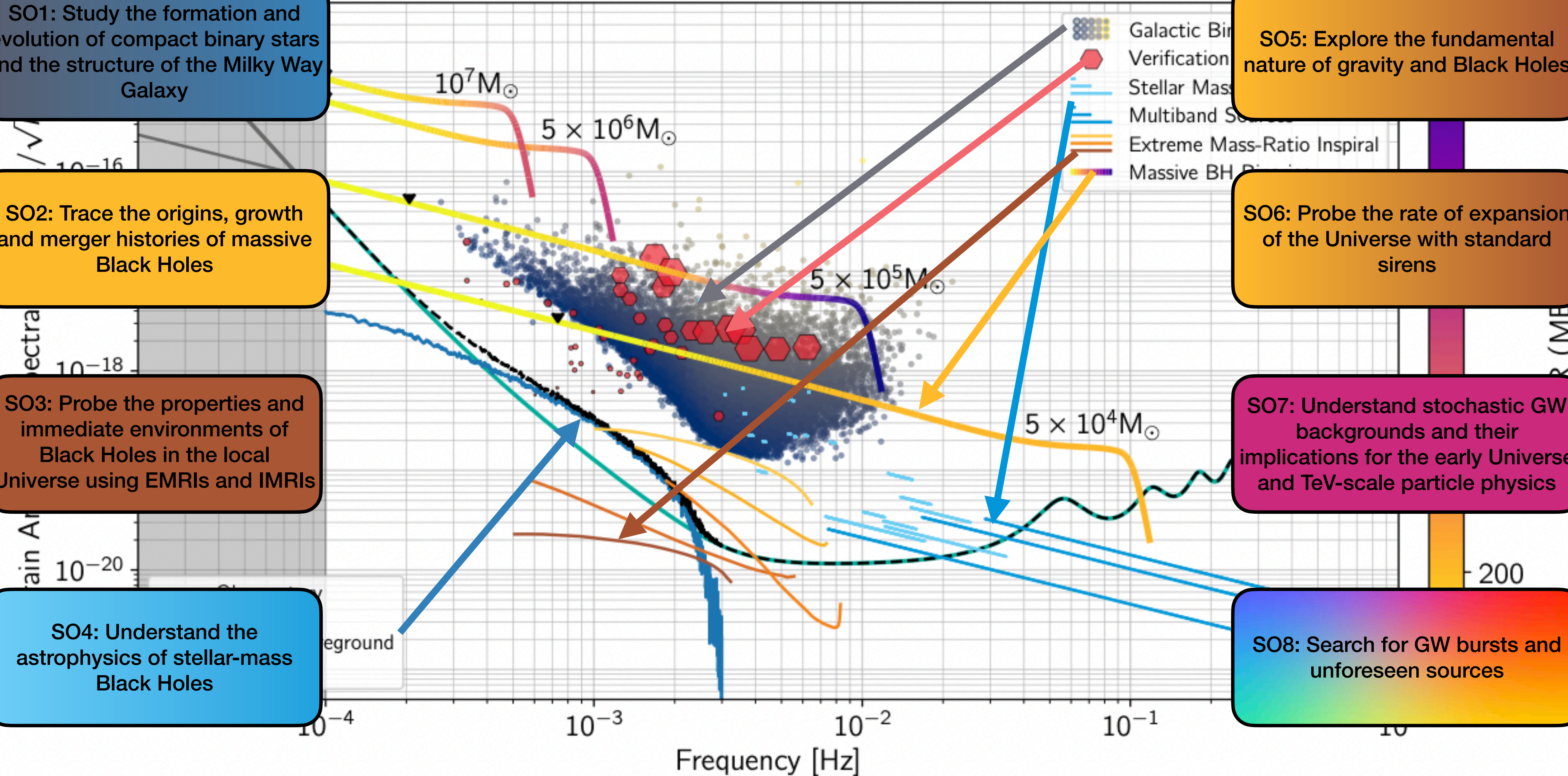
**SO4:** Understand the astrophysics of stellar-mass Black Holes

**SO5:** Explore the fundamental nature of gravity and Black Holes

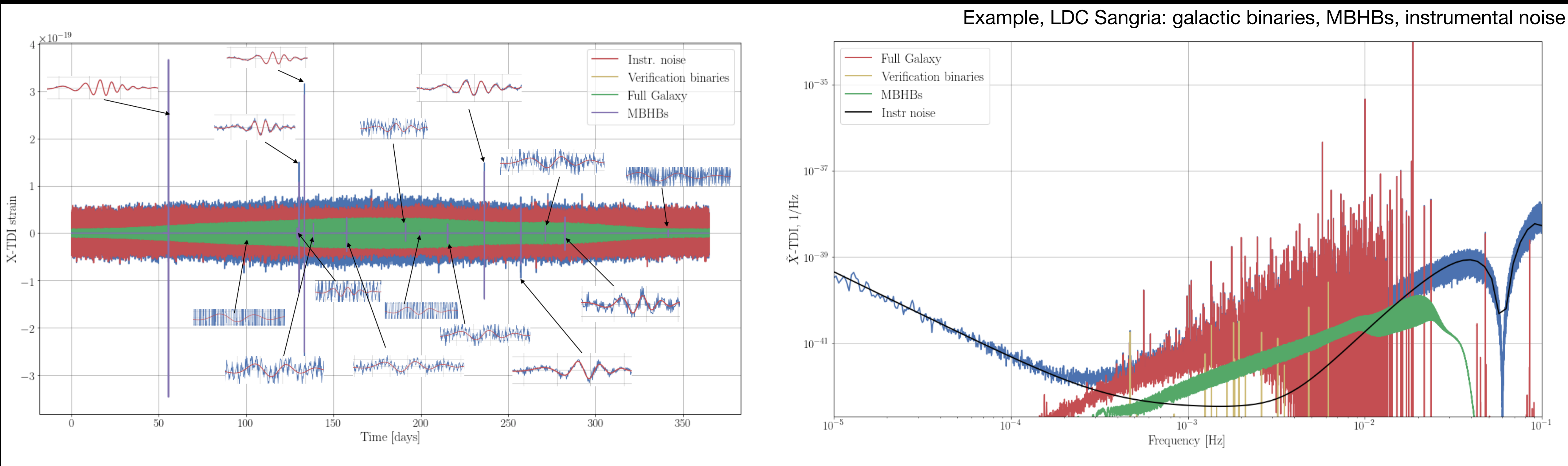
**SO6:** Probe the rate of expansion of the Universe with standard sirens

**SO7:** Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics

**SO8:** Search for GW bursts and unforeseen sources



# With great power come great data analysis challenges...



- LISA will continuously record signals from all directions, overlapping in time and/or frequency
- Some sources are expected to have very high SNR and be fairly obvious...
- ... and prototype solutions for the global fit do exist, based on the LISA Data challenges...
- ... but extracting all possible science from the real LISA data is far from a solved problem.
- Since adoption: focused coordinated efforts from the distributed data processing center (DDPC) and NASA science ground segment (NSGS).

# Mission overview

Astrophysical System



Understanding...



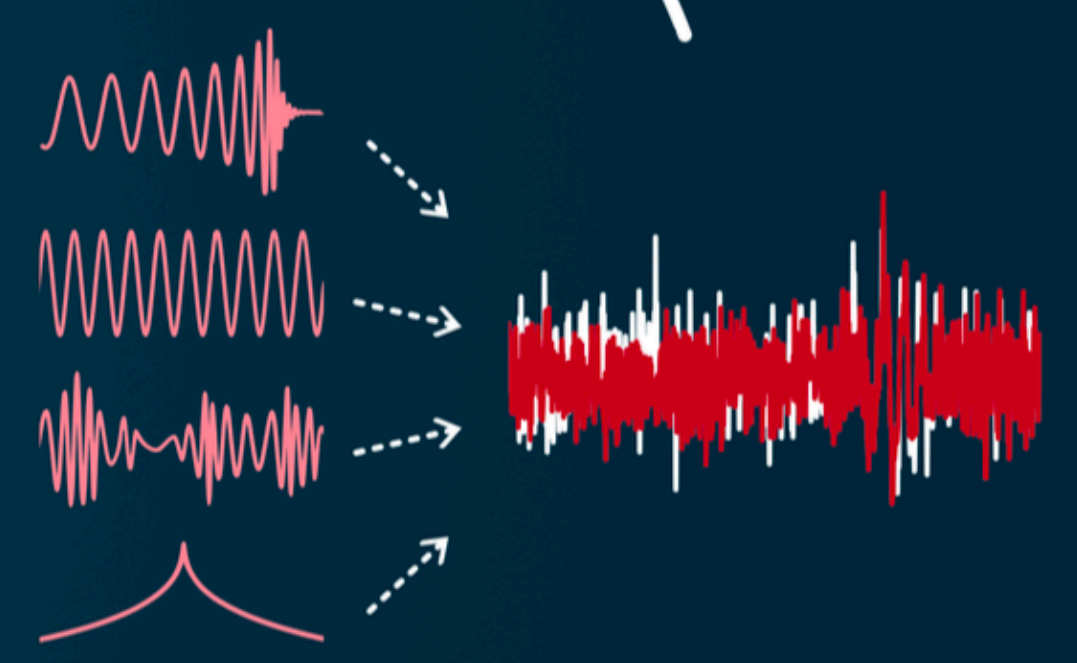
Science Investigations

Level 3 data  
Level 2 data

Sources and Catalogues



Fitting Models



Gravitational Wave Data



Level 1 data

## LISA MISSION CONCEPT



Doppler Shift Measurements



Level 0 data

Processing Spacecraft Signals



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Thank you for your attention!