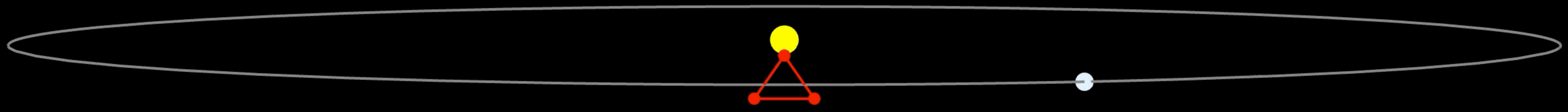
Overview of the LISA detector and its future observational capabilities

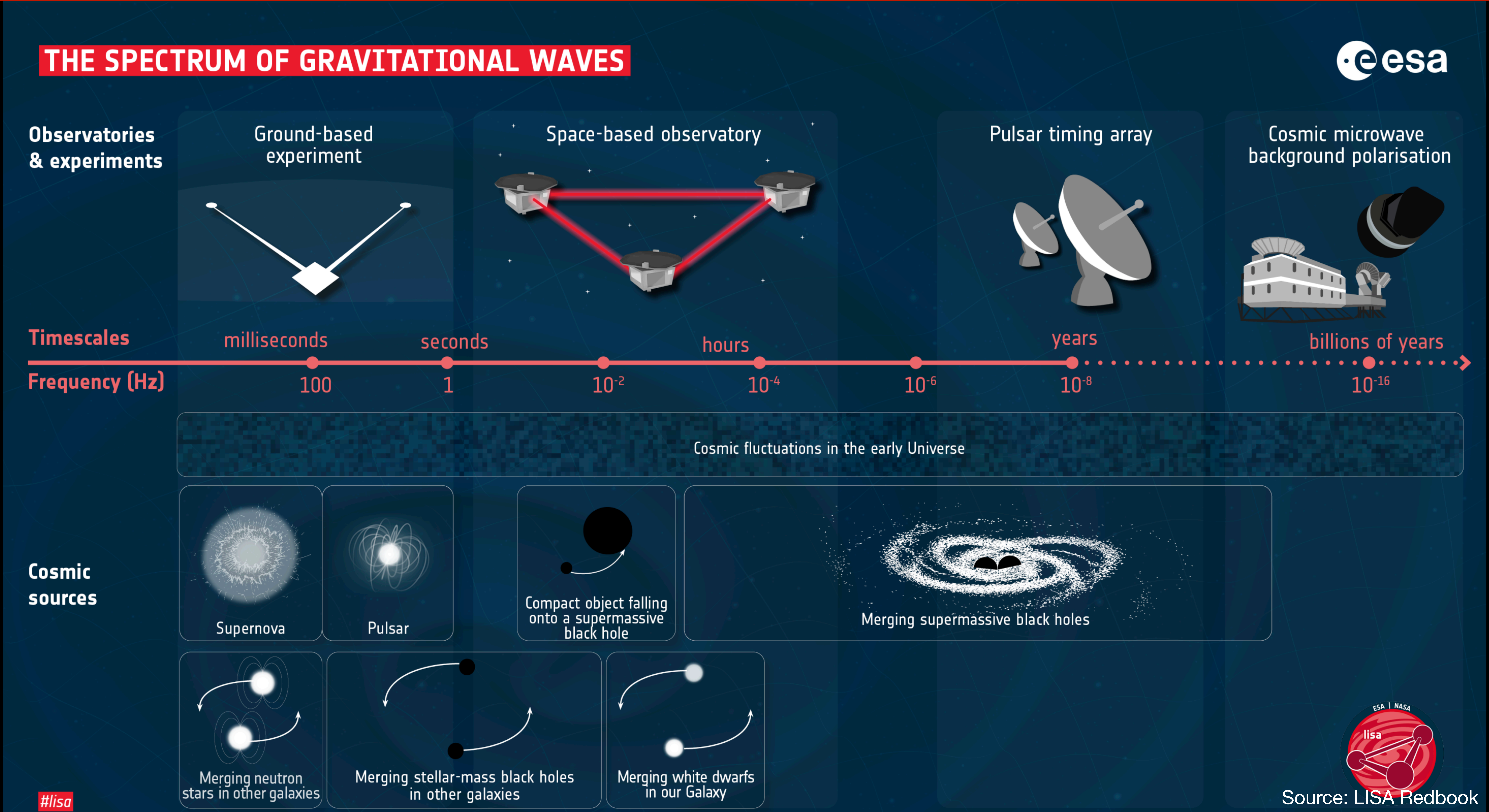
GraSP24, 2024-10-23, Olaf Hartwig

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 $\Longrightarrow$ 💰, 🏗️, **planned launch ∼ 2035**
- Details: https://www.cosmos.esa.int/web/lisa/lisa-redbook

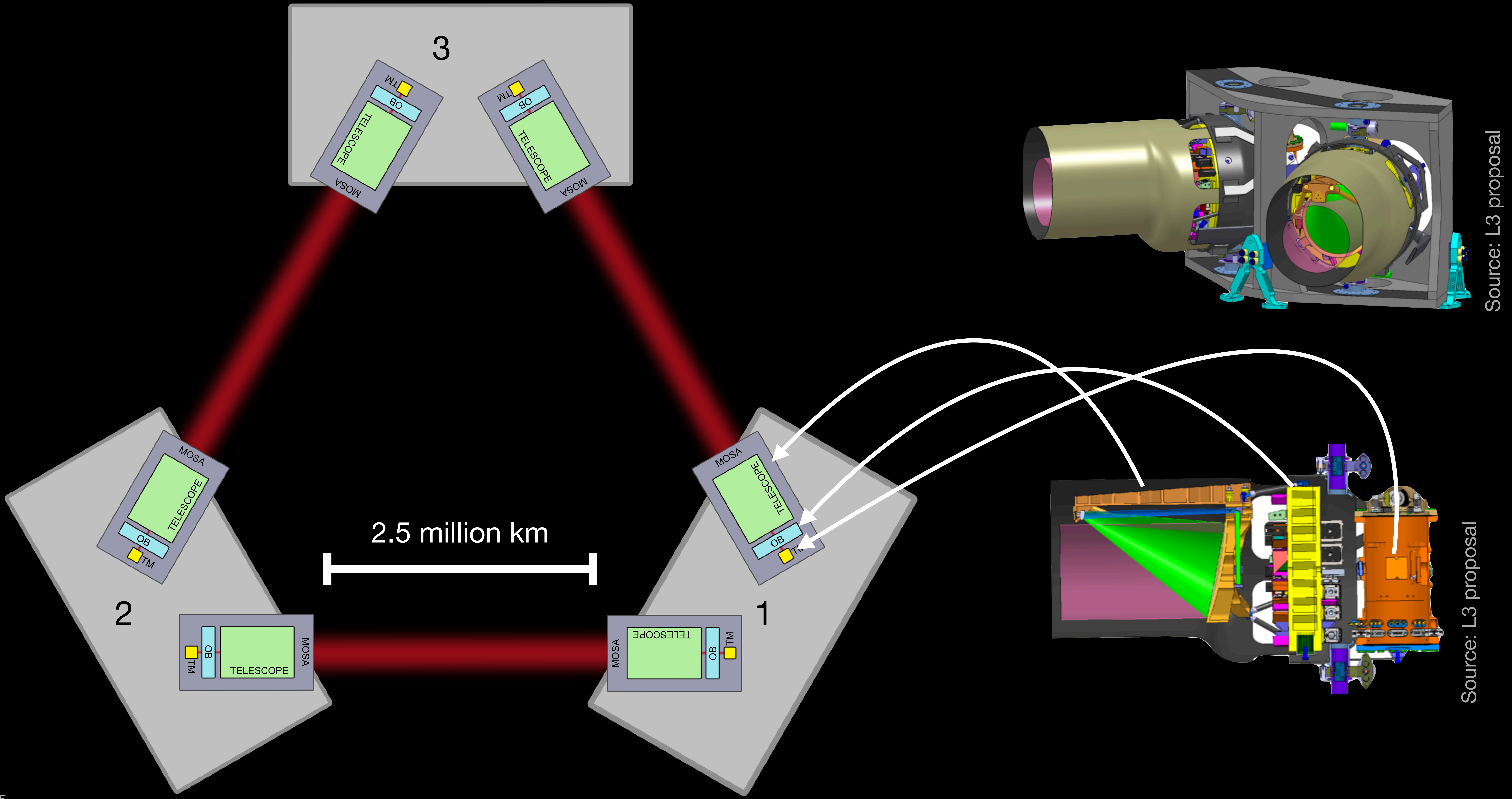
Why go to space?



Source: LISA Redbook

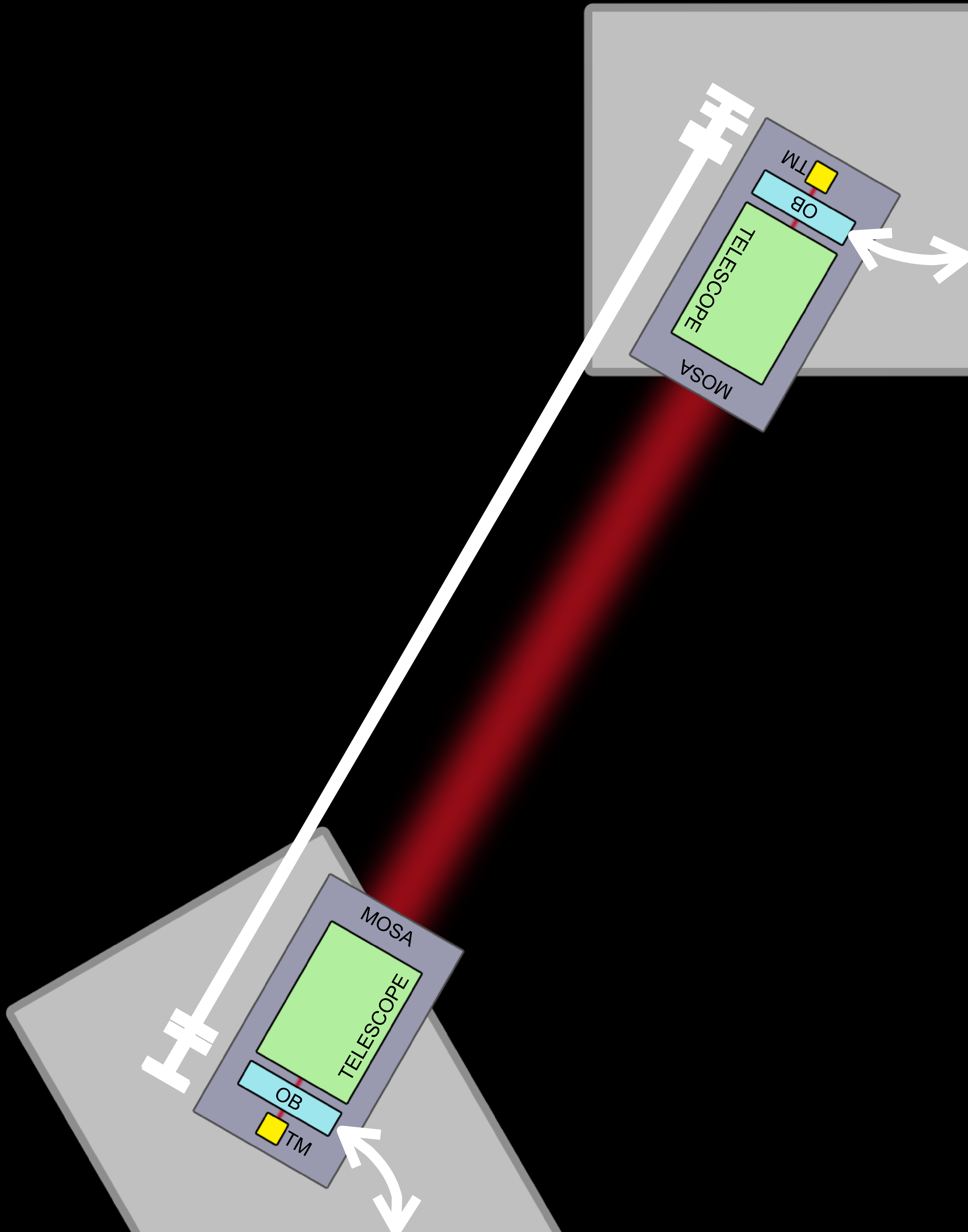
Technical overview

LISA constellation overview



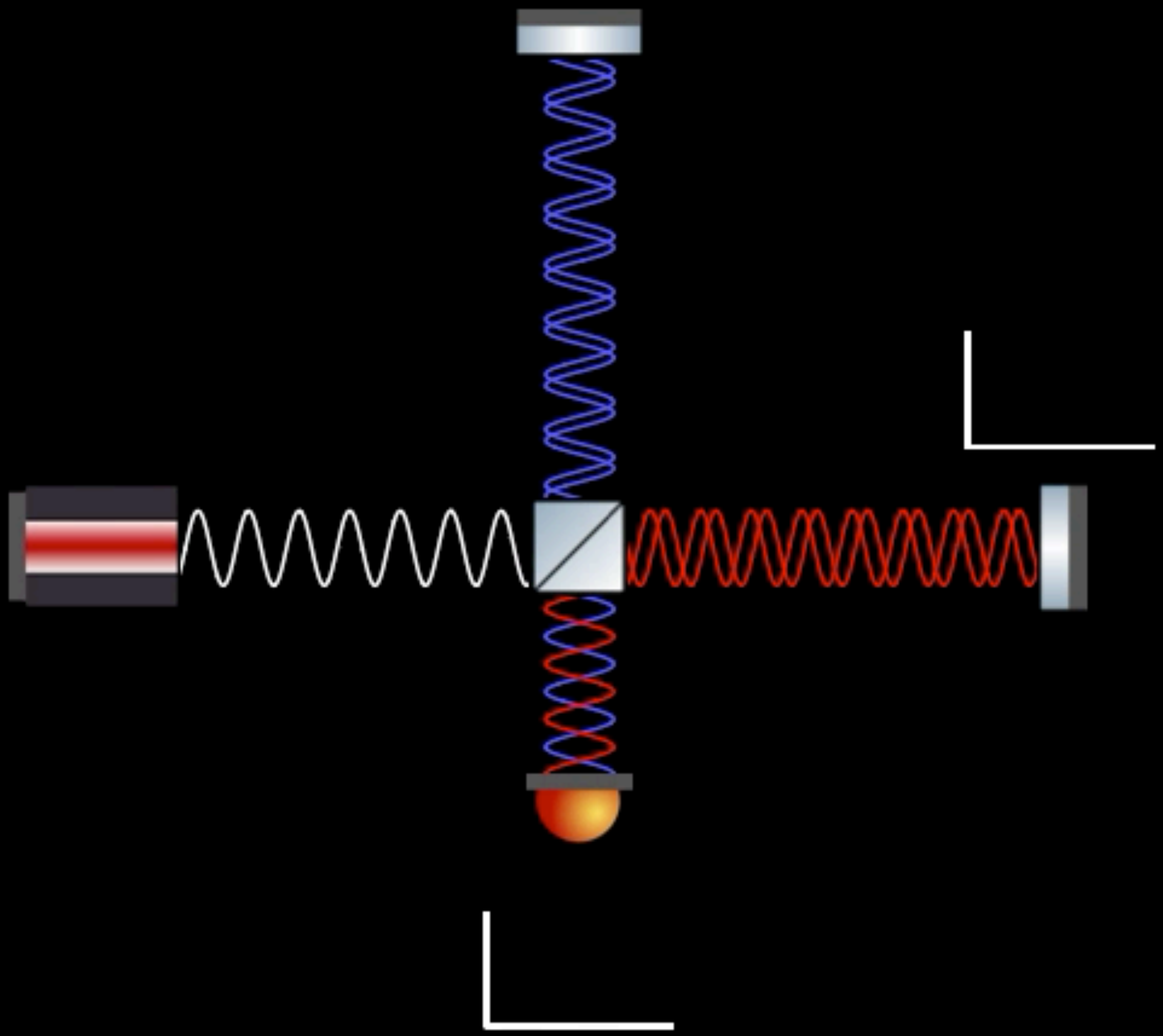
LISA constellation overview

- 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!

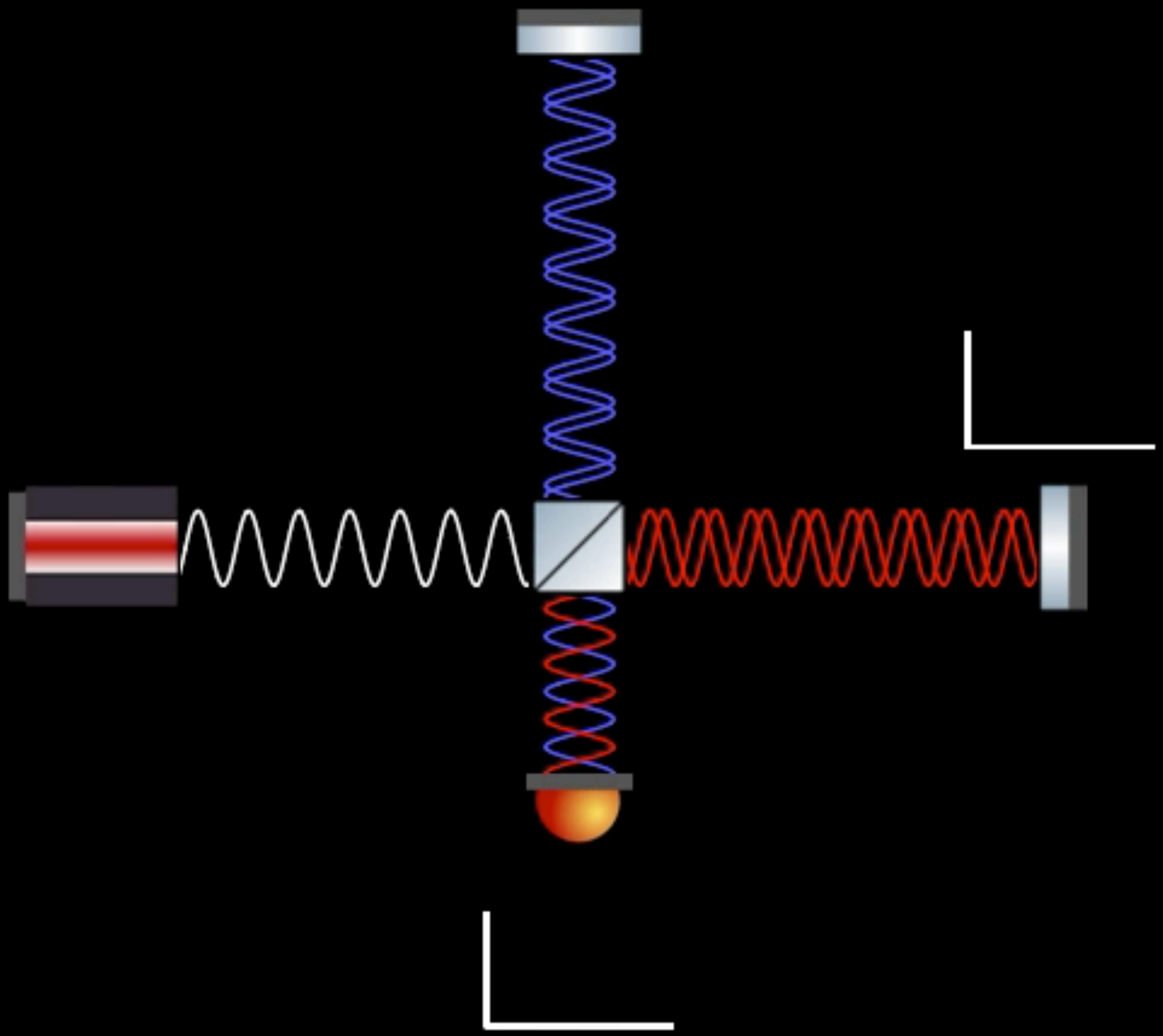


Suppressed noise sources

Laser noise cancellation in interferometers



Laser noise cancellation in interferometers



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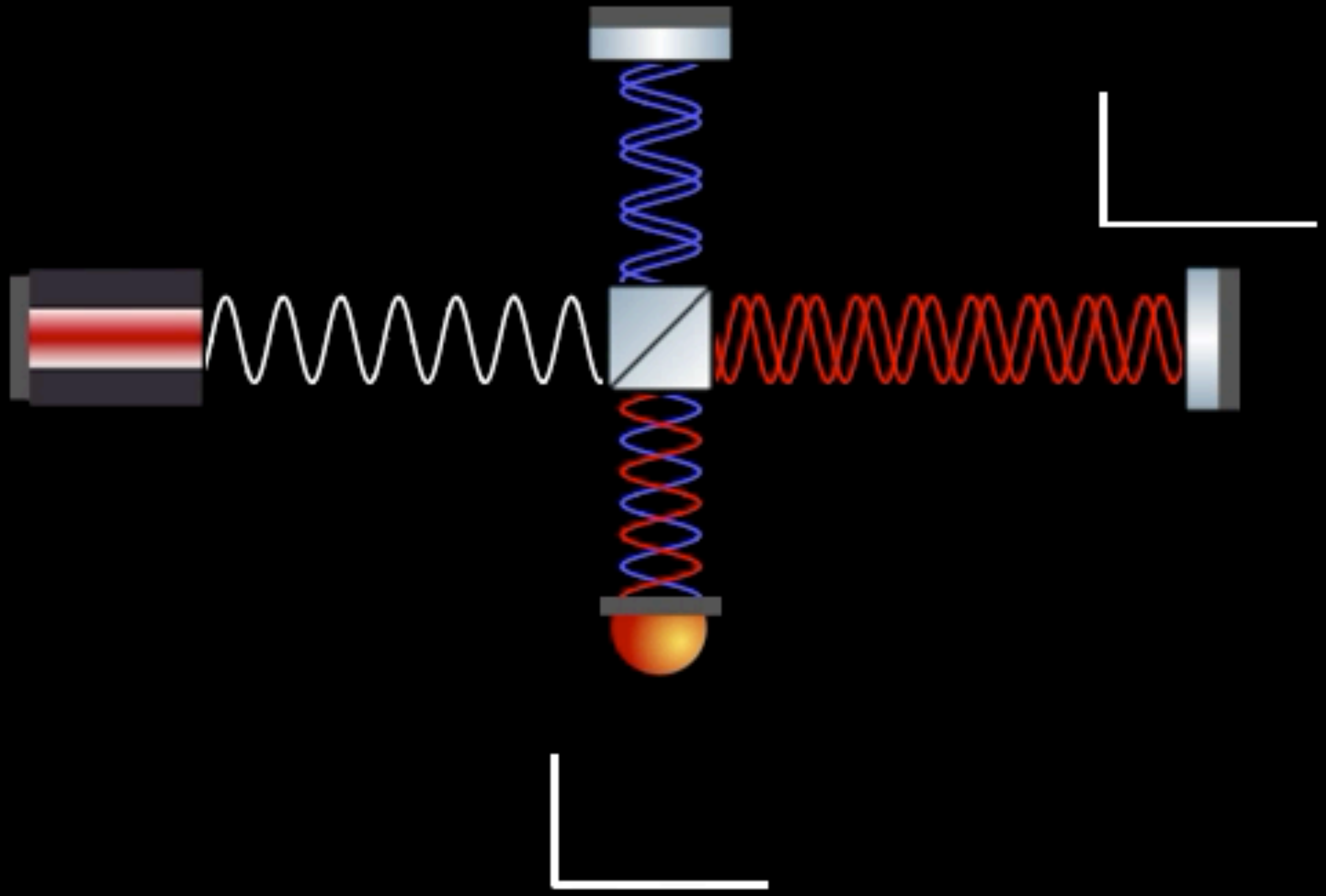
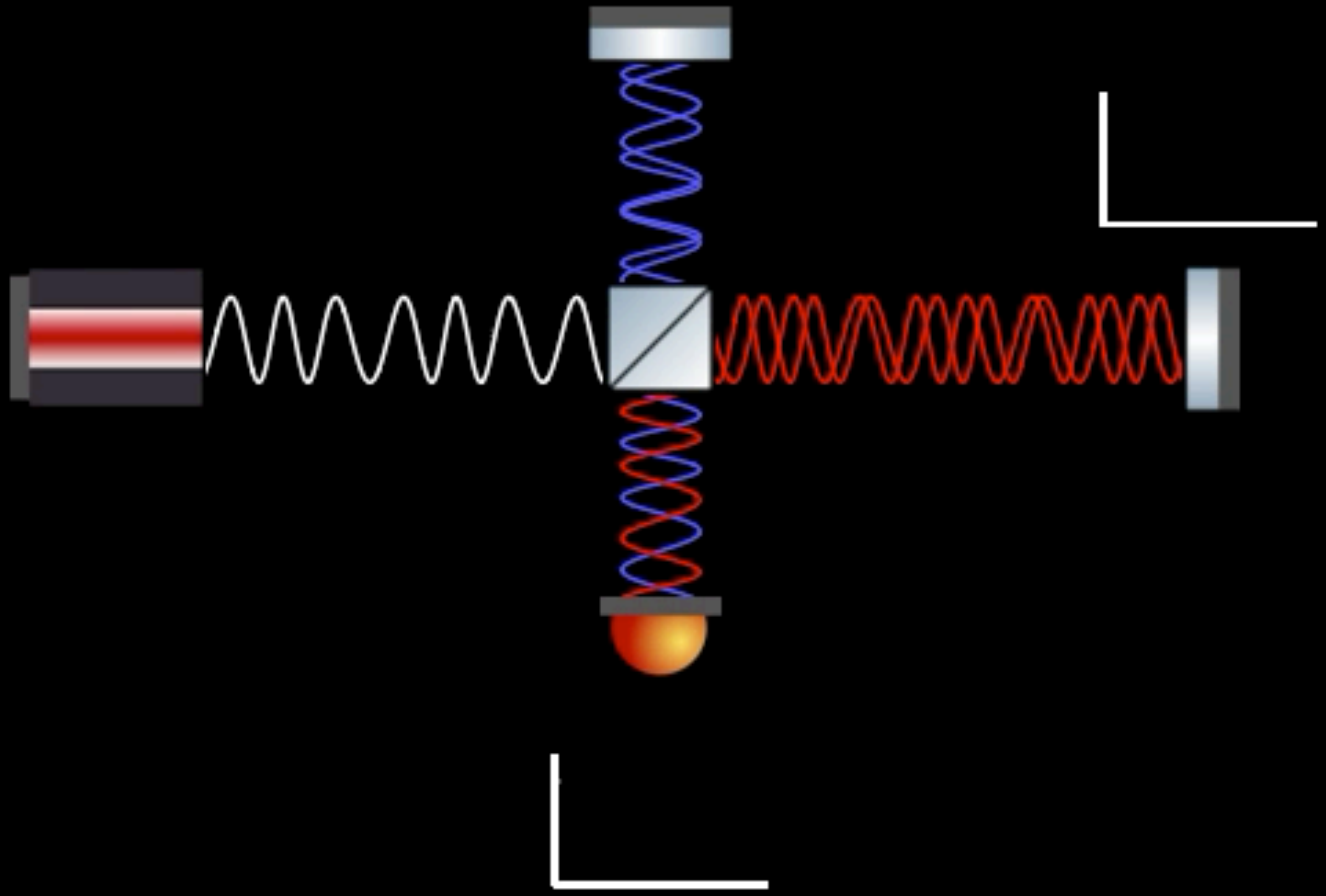
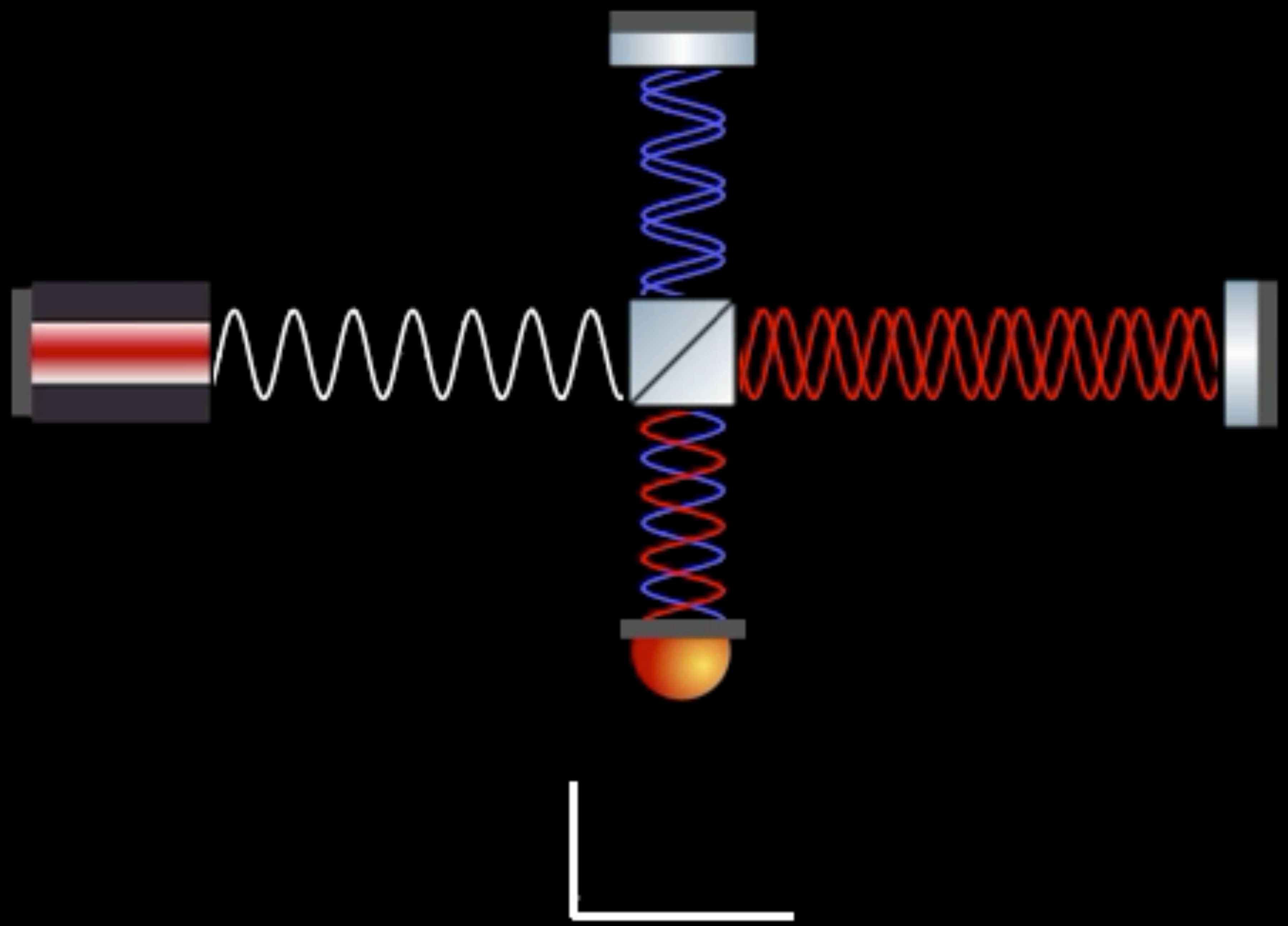
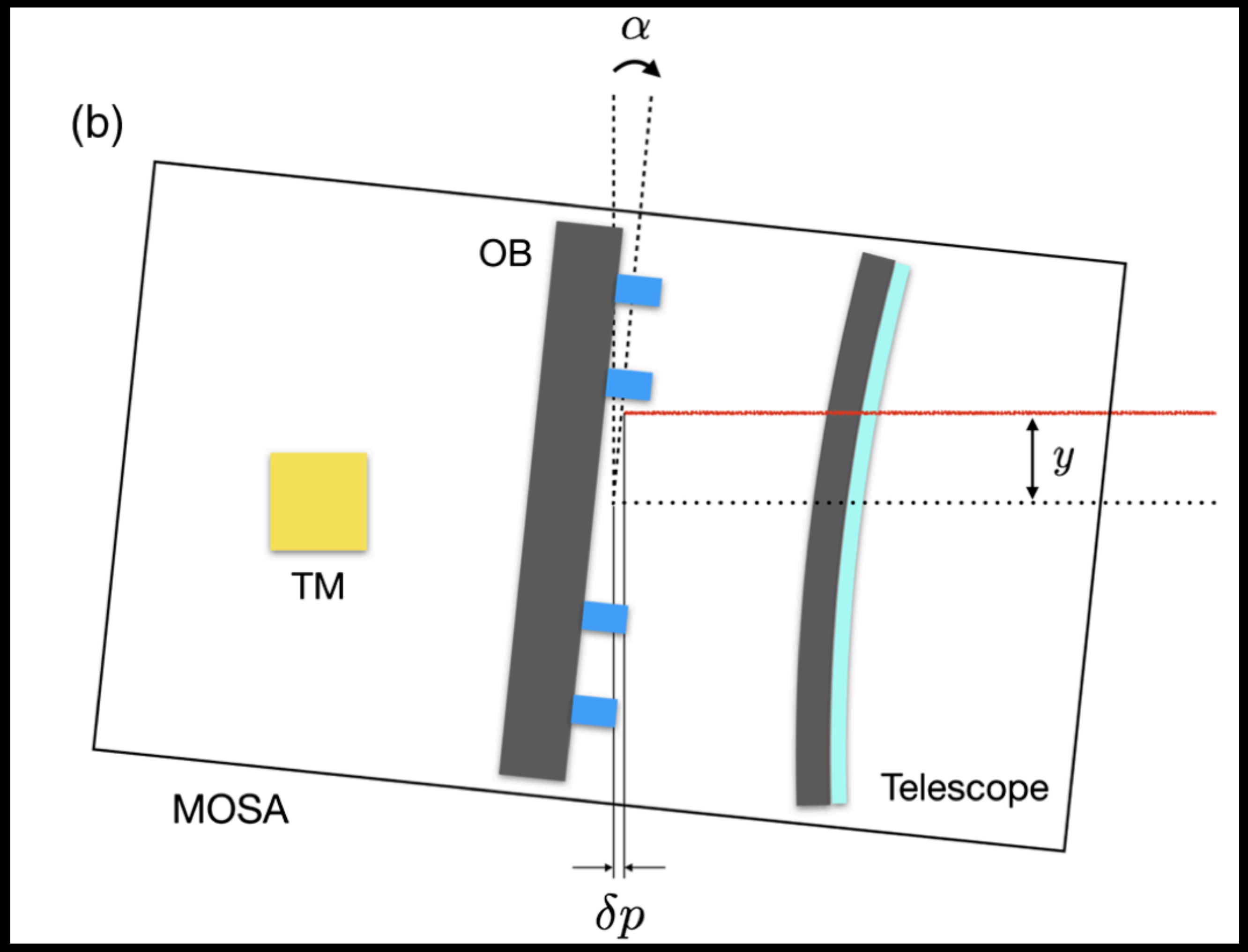


Laser noise cancellation in interferometers



Further complications: beyond laser noise suppression



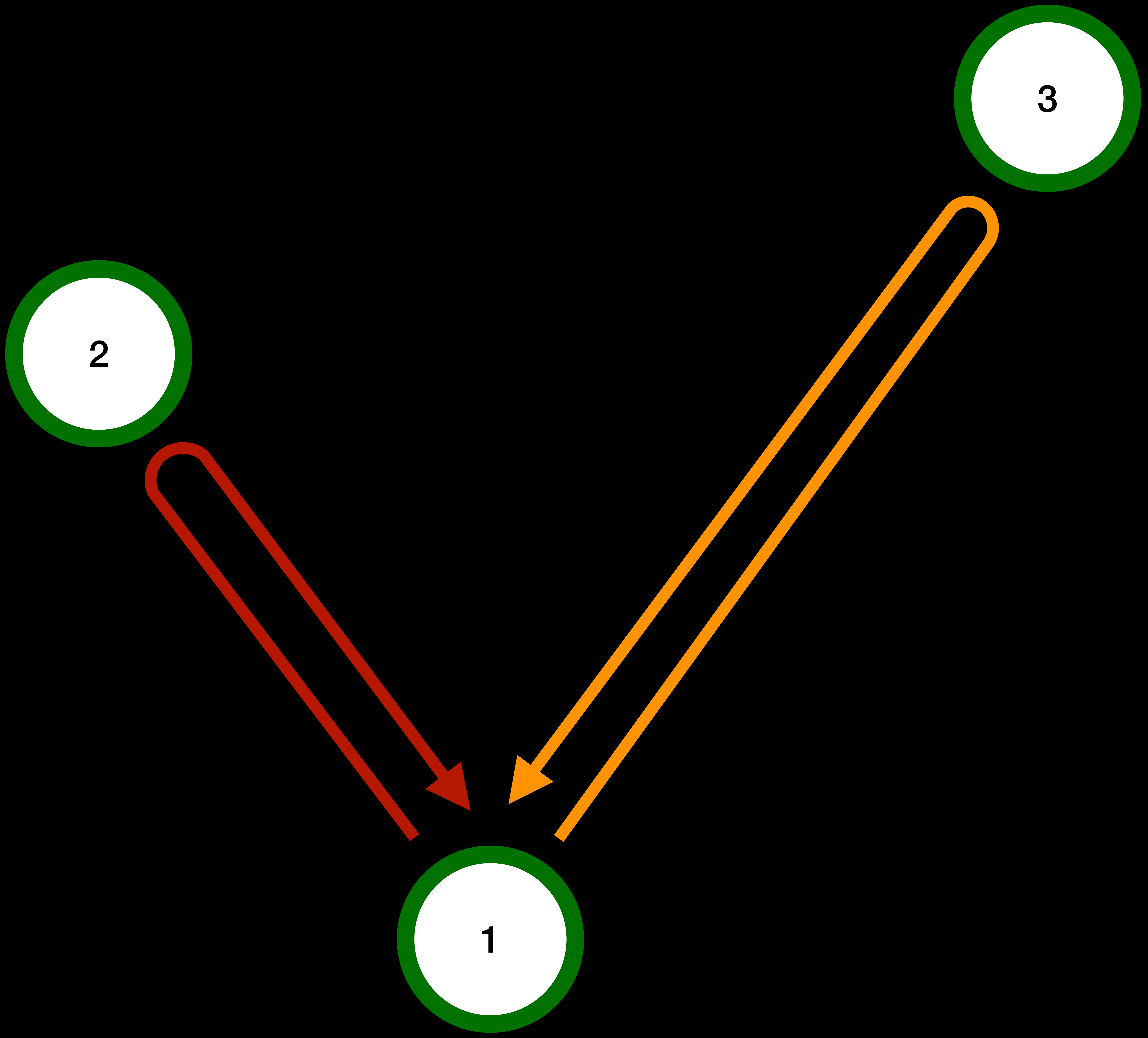


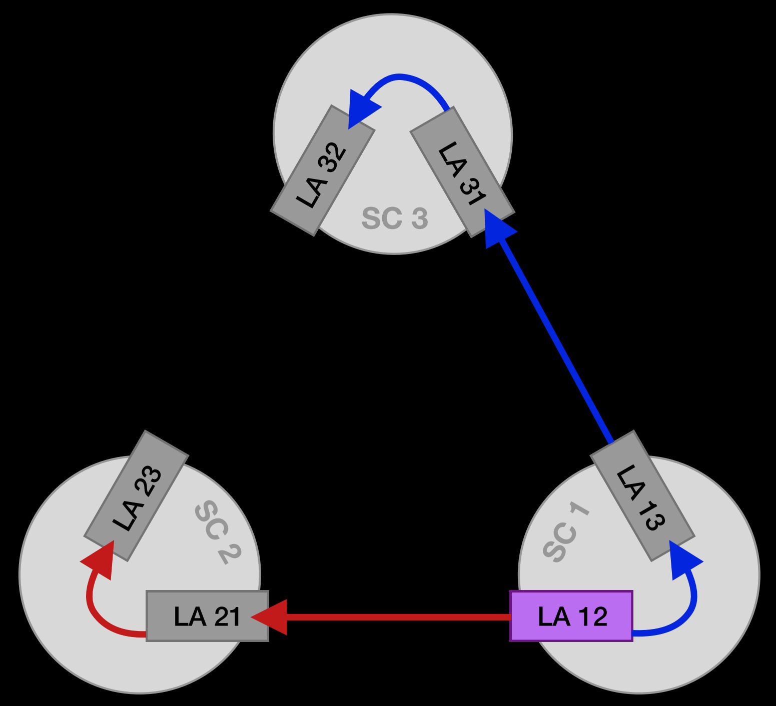
Source: 10.1103/PhysRevD.106.042005

- 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 ≈ **66 interferometric measurements** with **ground tracking information** and **auxiliary sensors** to produce **3 synchronized scientific variables**

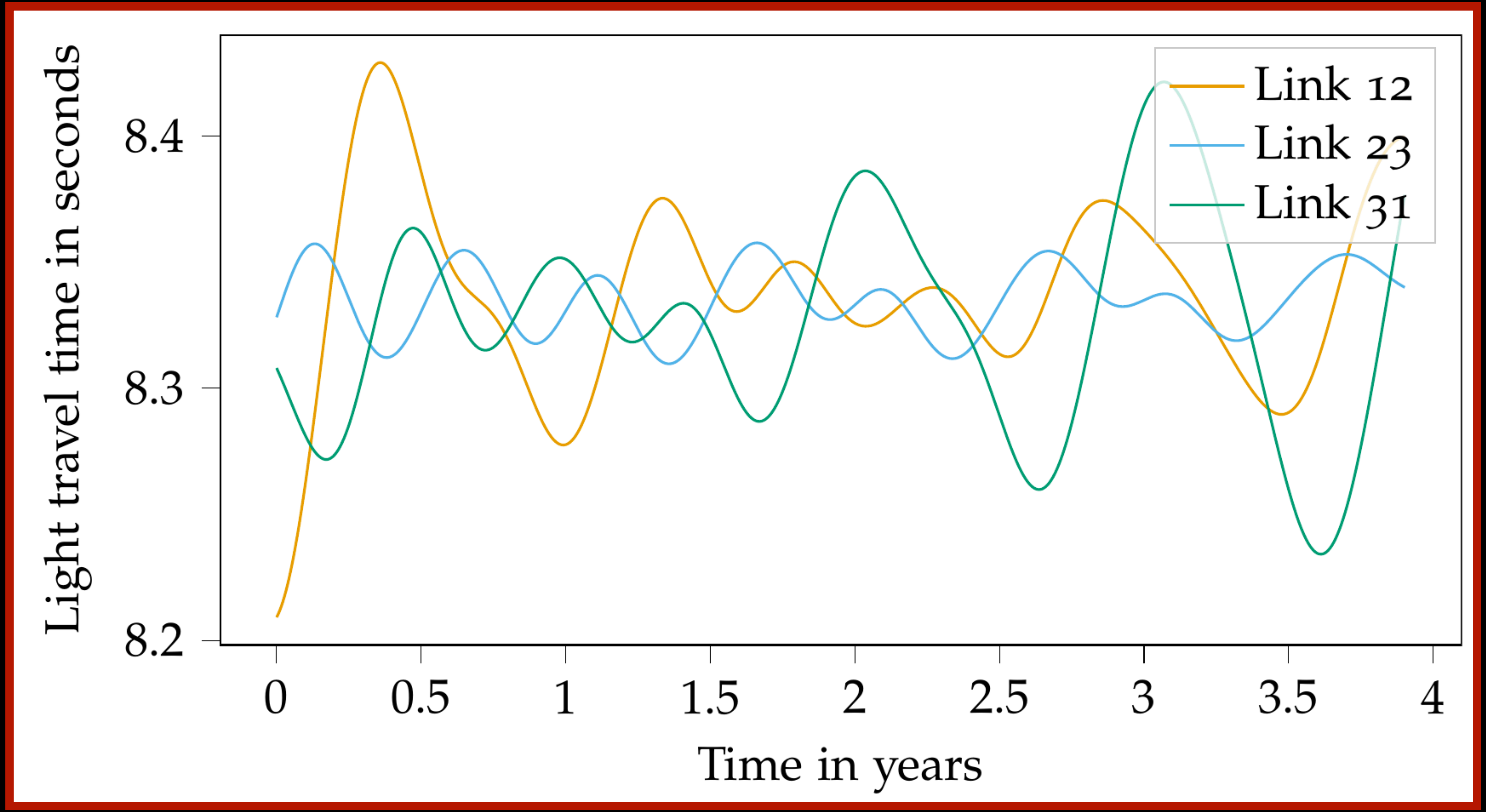
Time delay interferometry

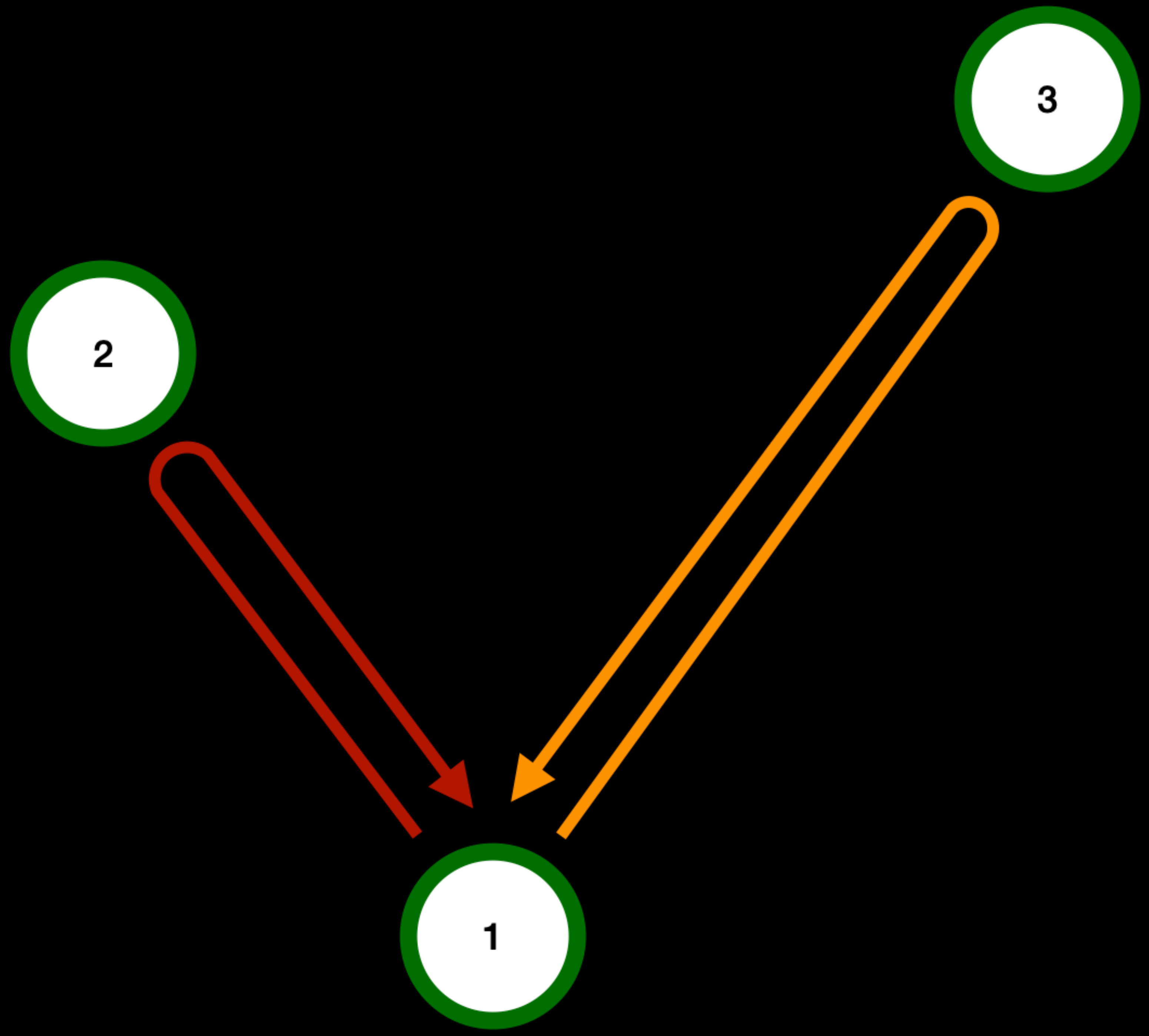
Laser noise cancellation in LISA





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 $\delta t = \delta t_1 - \delta t_2$)

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

Residual laser noise in LISA

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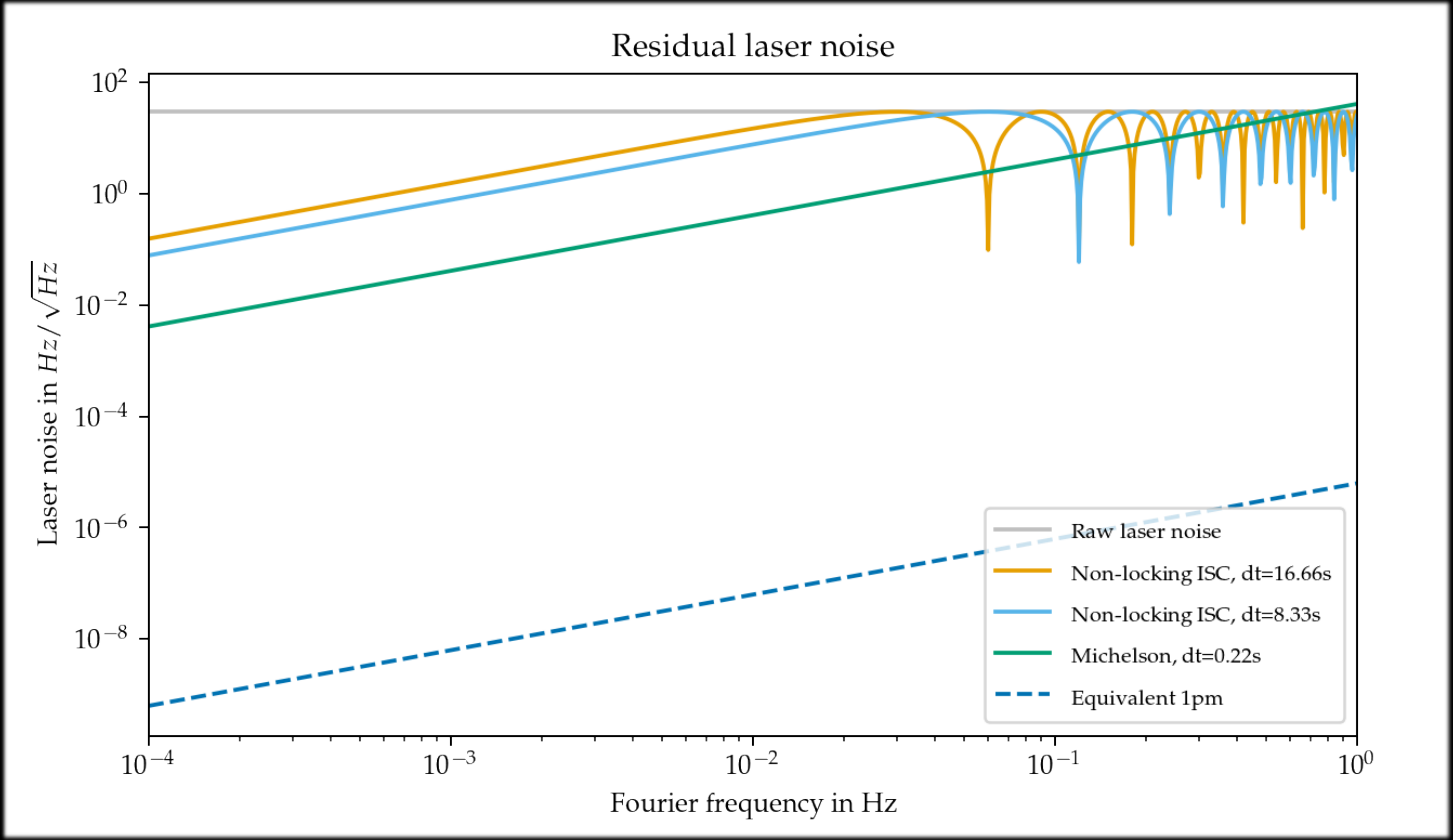
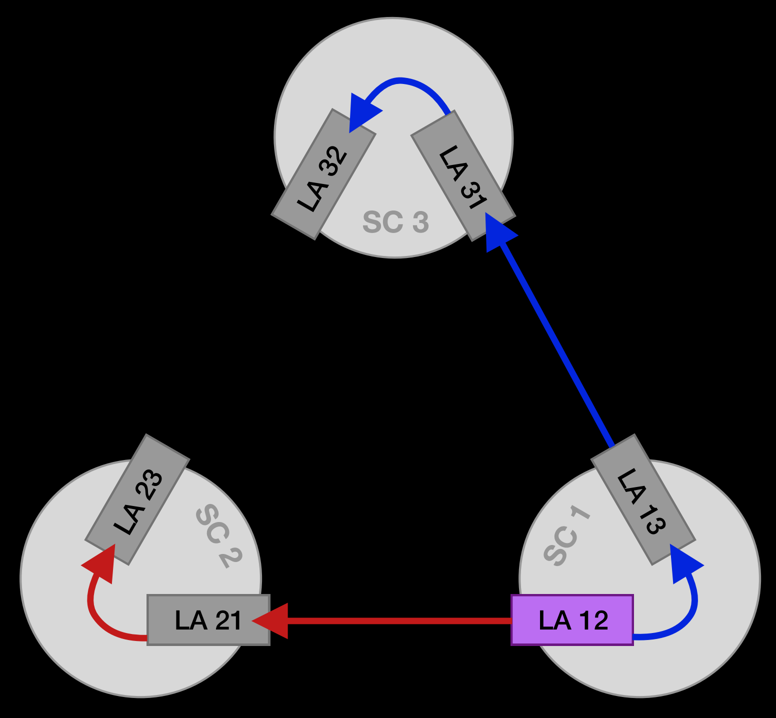
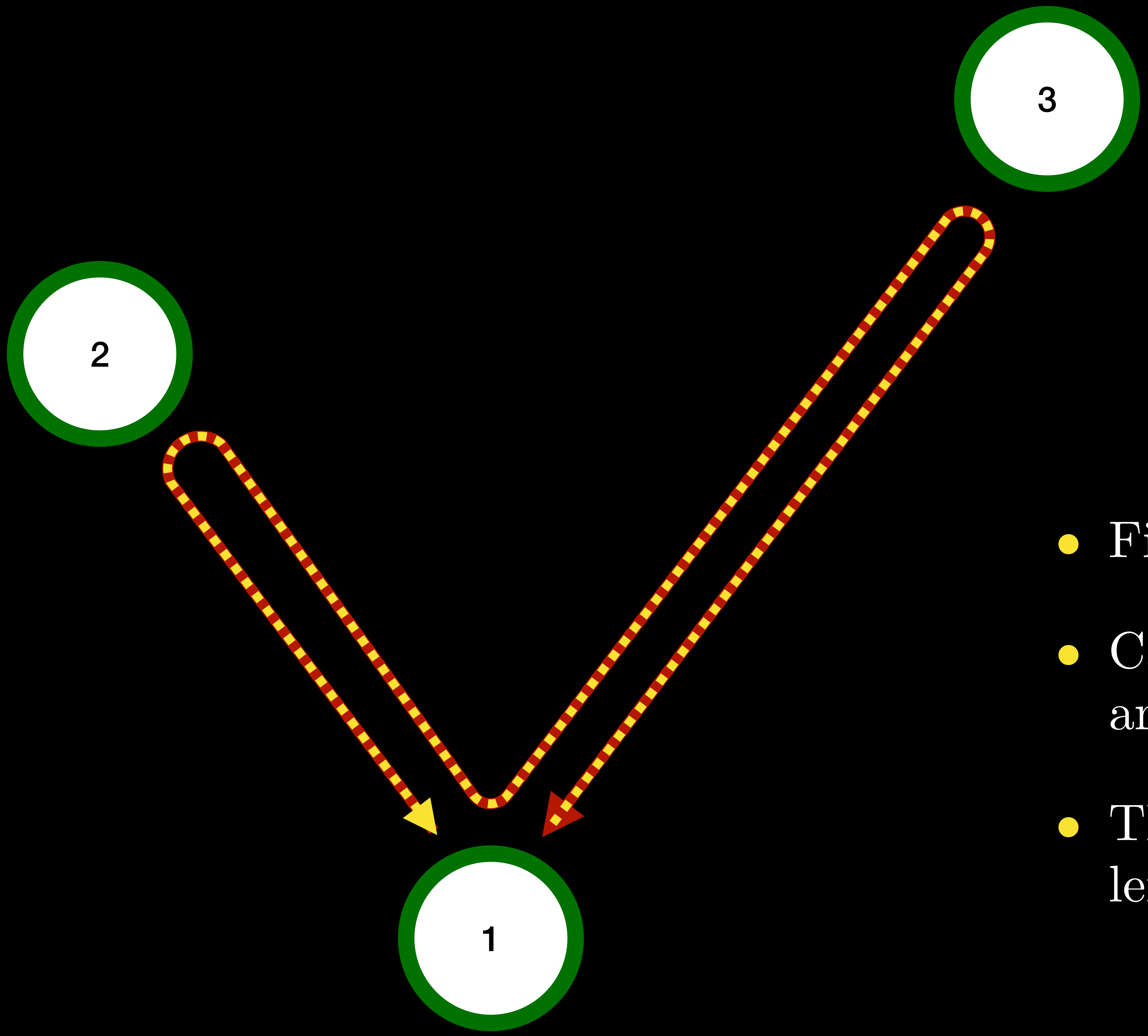




Note: Illustrative, neither laser noise nor actual requirement are white across the band

Time-Delay Interferometry



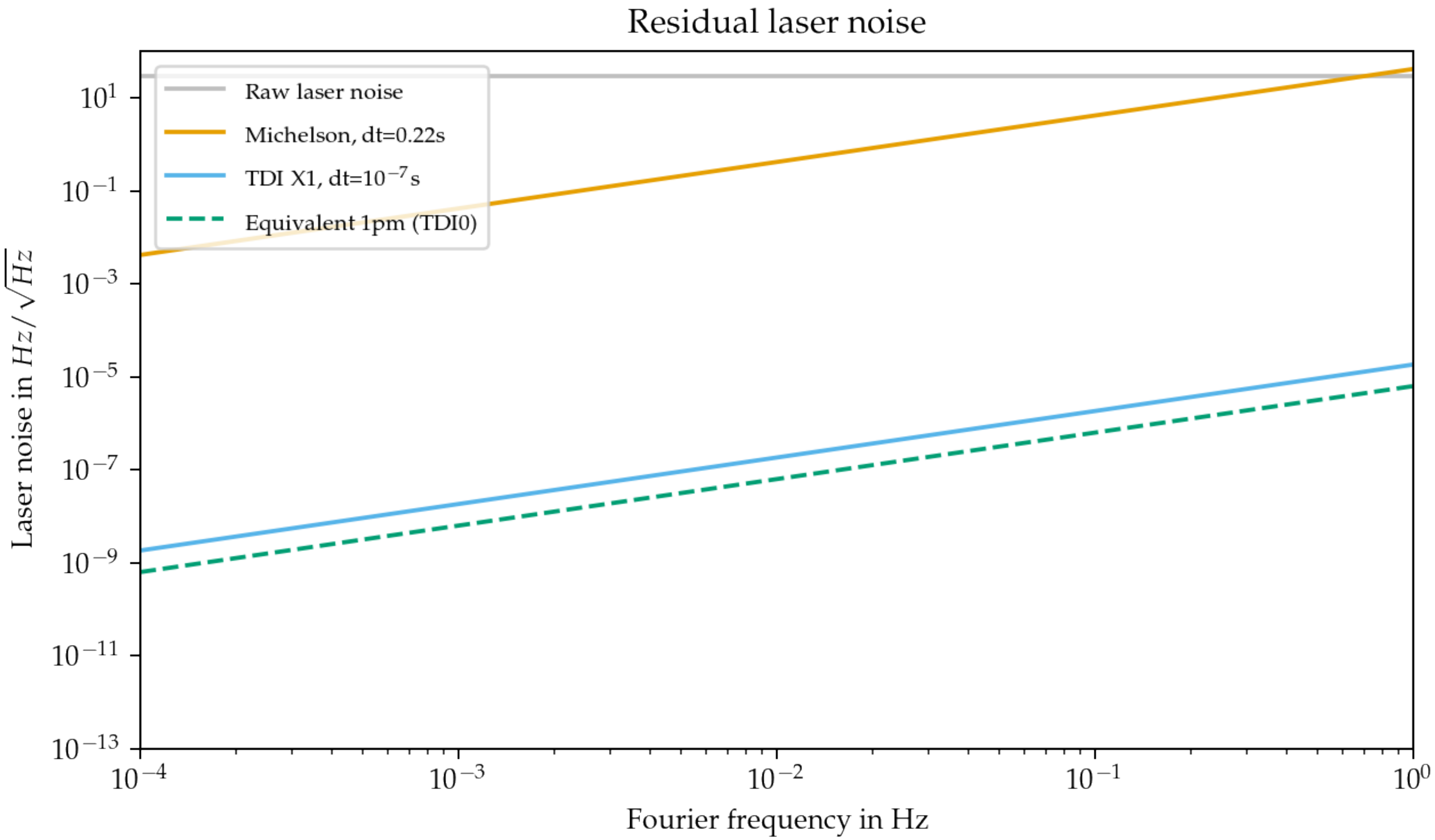
- First proposed in [Tinto et al., 1999]
- Cancel laser noise by constructing equal arm interferometer in post-processing
- This is an example for constant arm lengths (1st generation TDI)

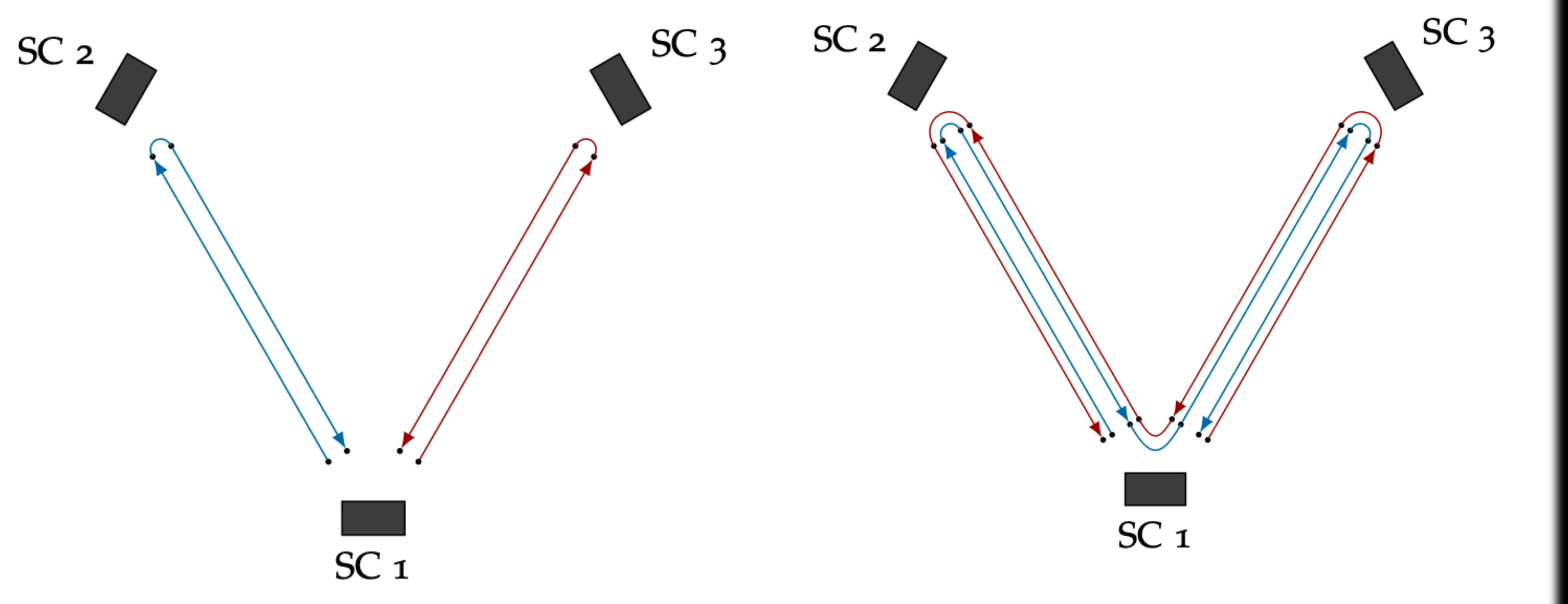
See living review [Tinto & Dhurandhar, 2020] for detailed references on TDI
First reference in history section (not quite TDI): [Faller and Bender, 1984]

Residual laser noise in LISA

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

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





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

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

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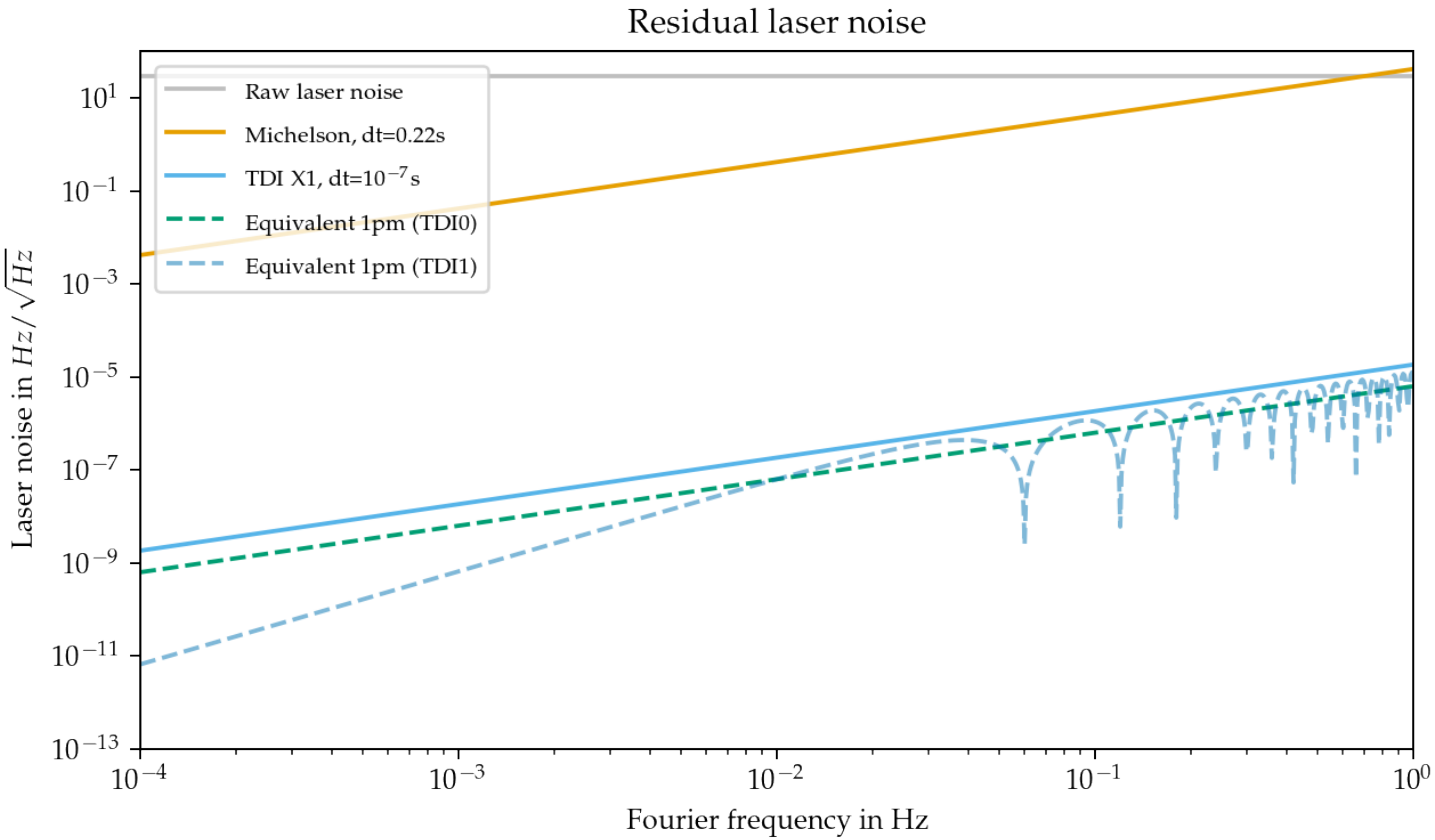

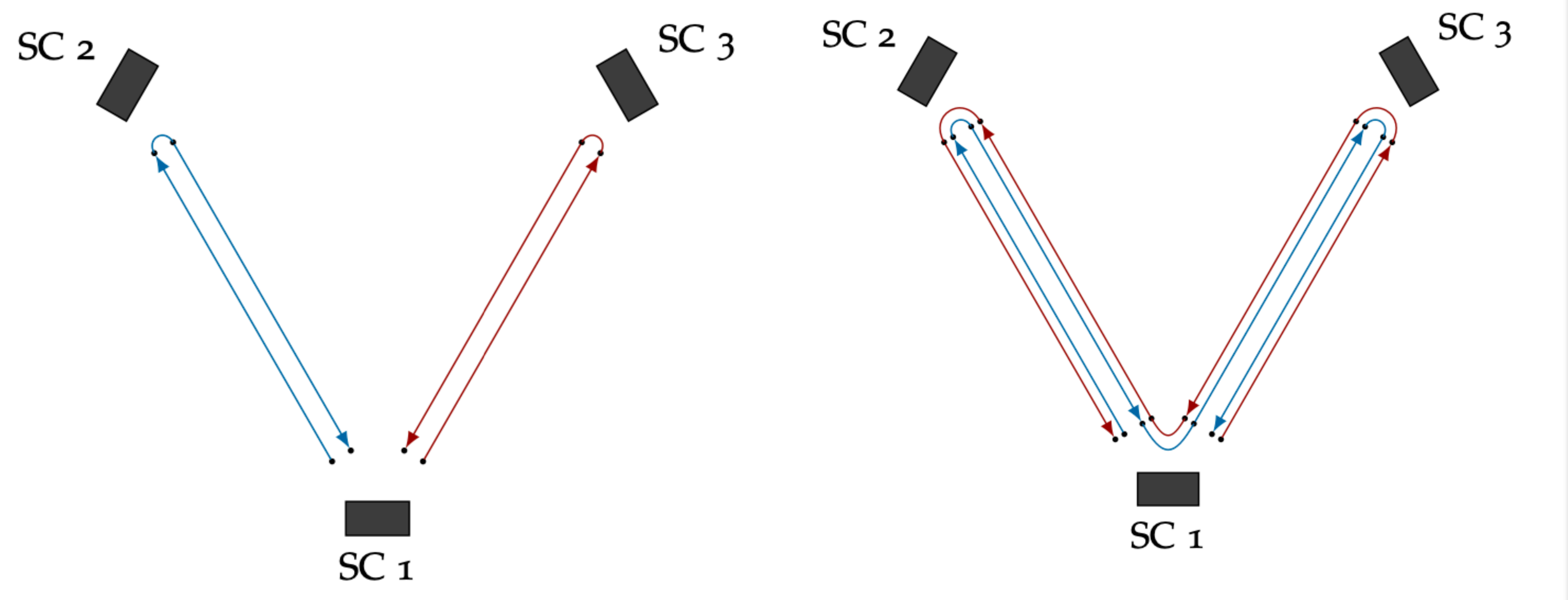

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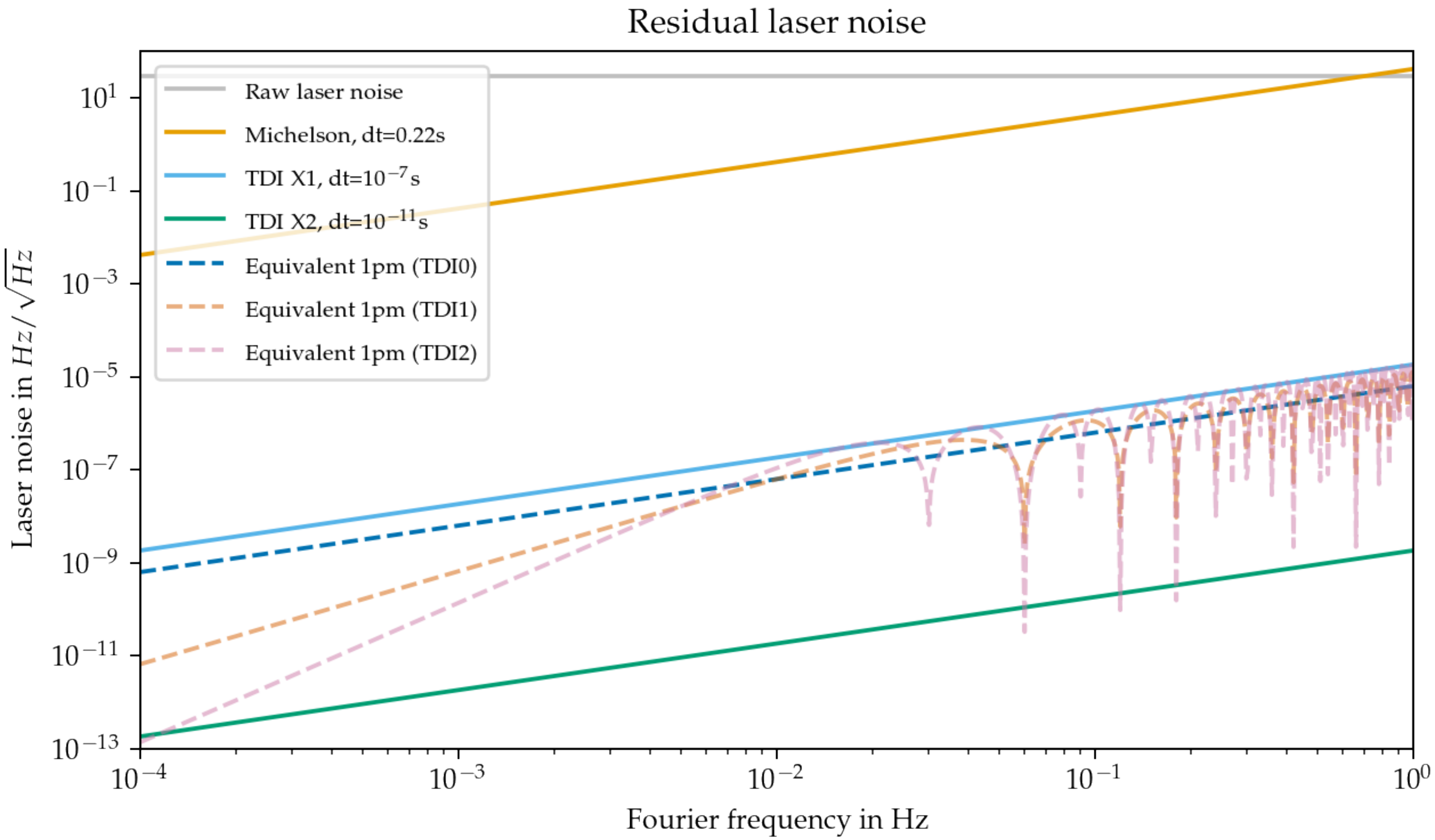

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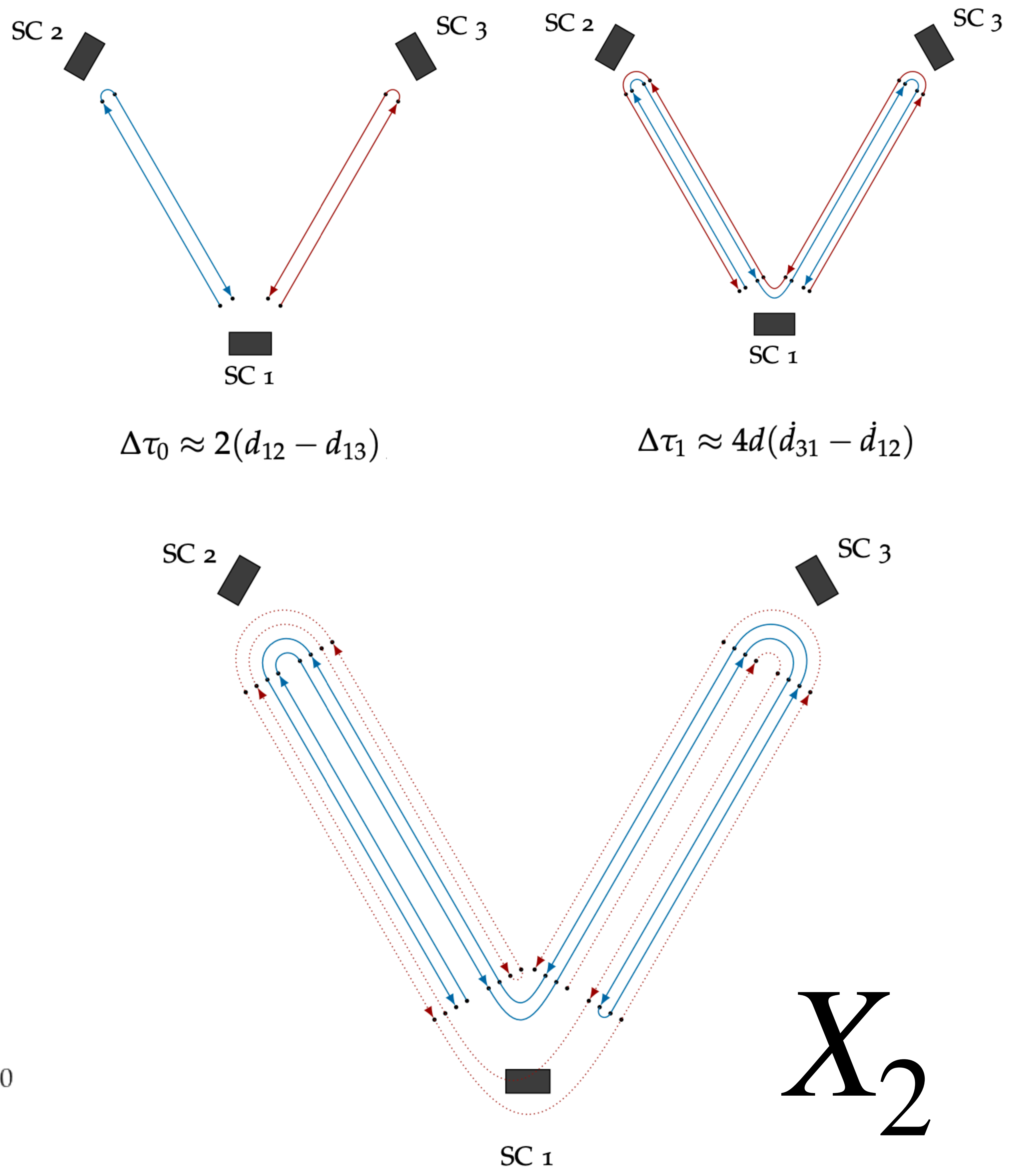


$\Delta\tau_0 \approx 2(d_{12} - d_{13})$

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

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

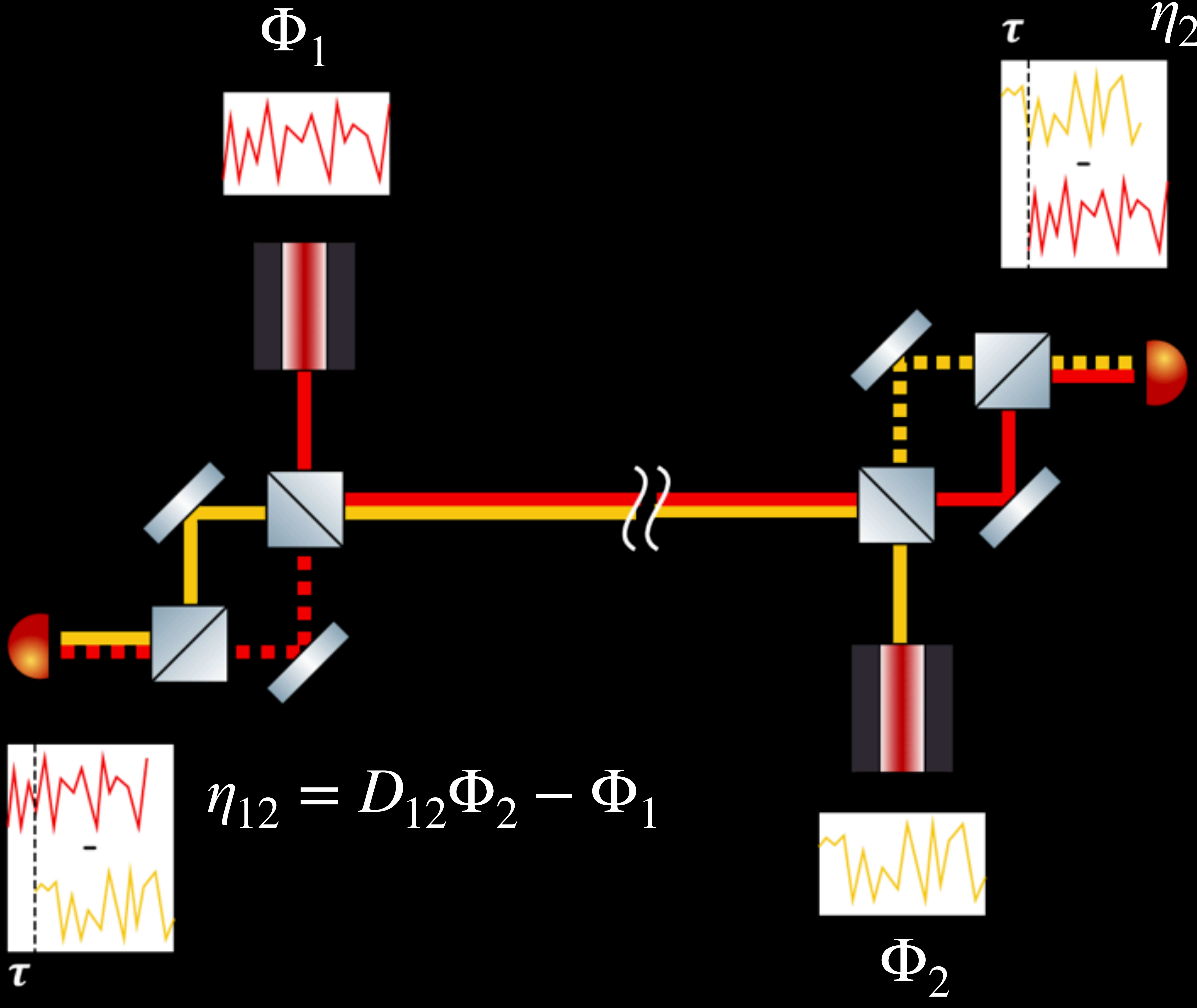
X_2

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

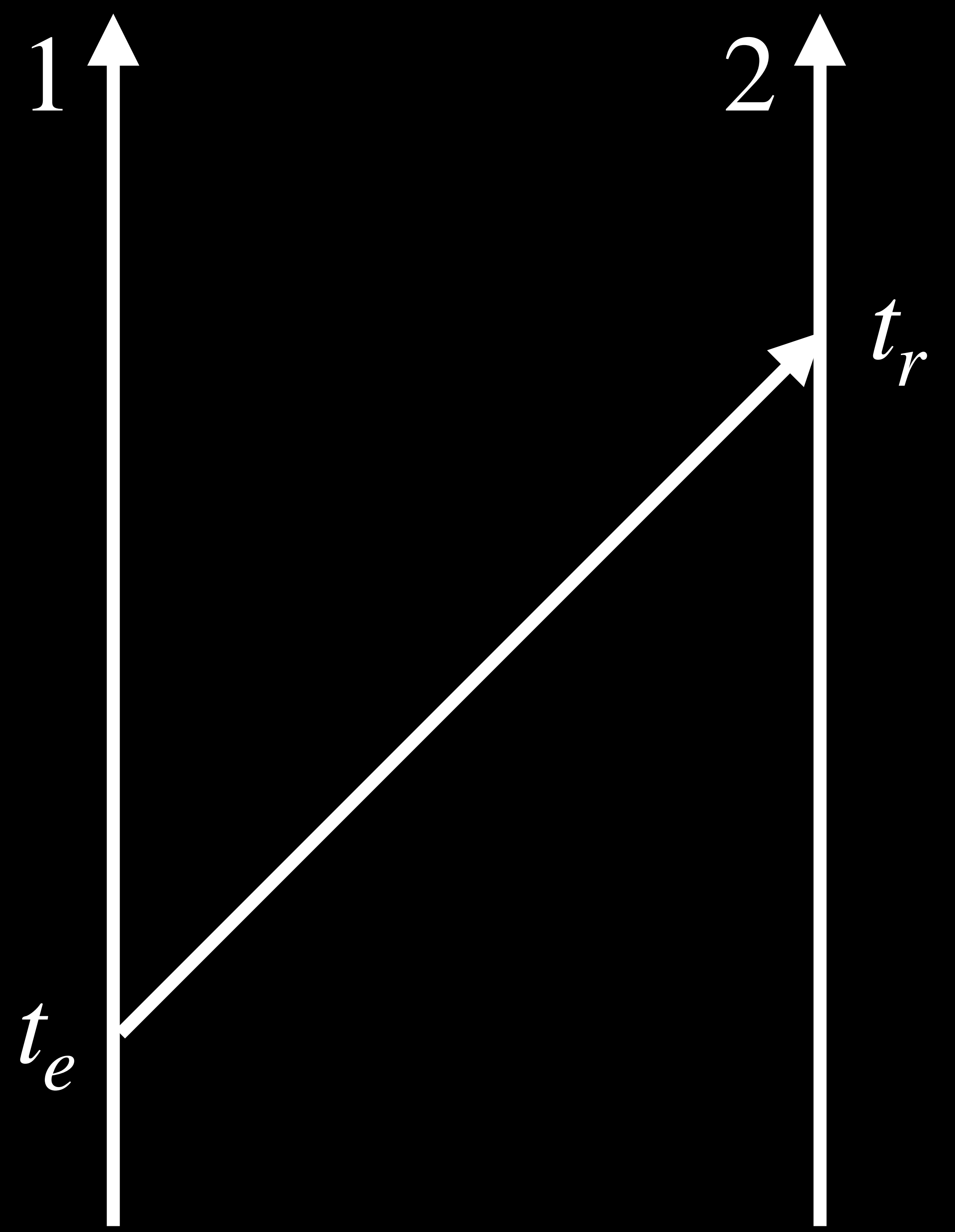
How does TDI work, in practice?

TDI toy model

$$\eta_{21} = D_{21}\Phi_1 - \Phi_2$$

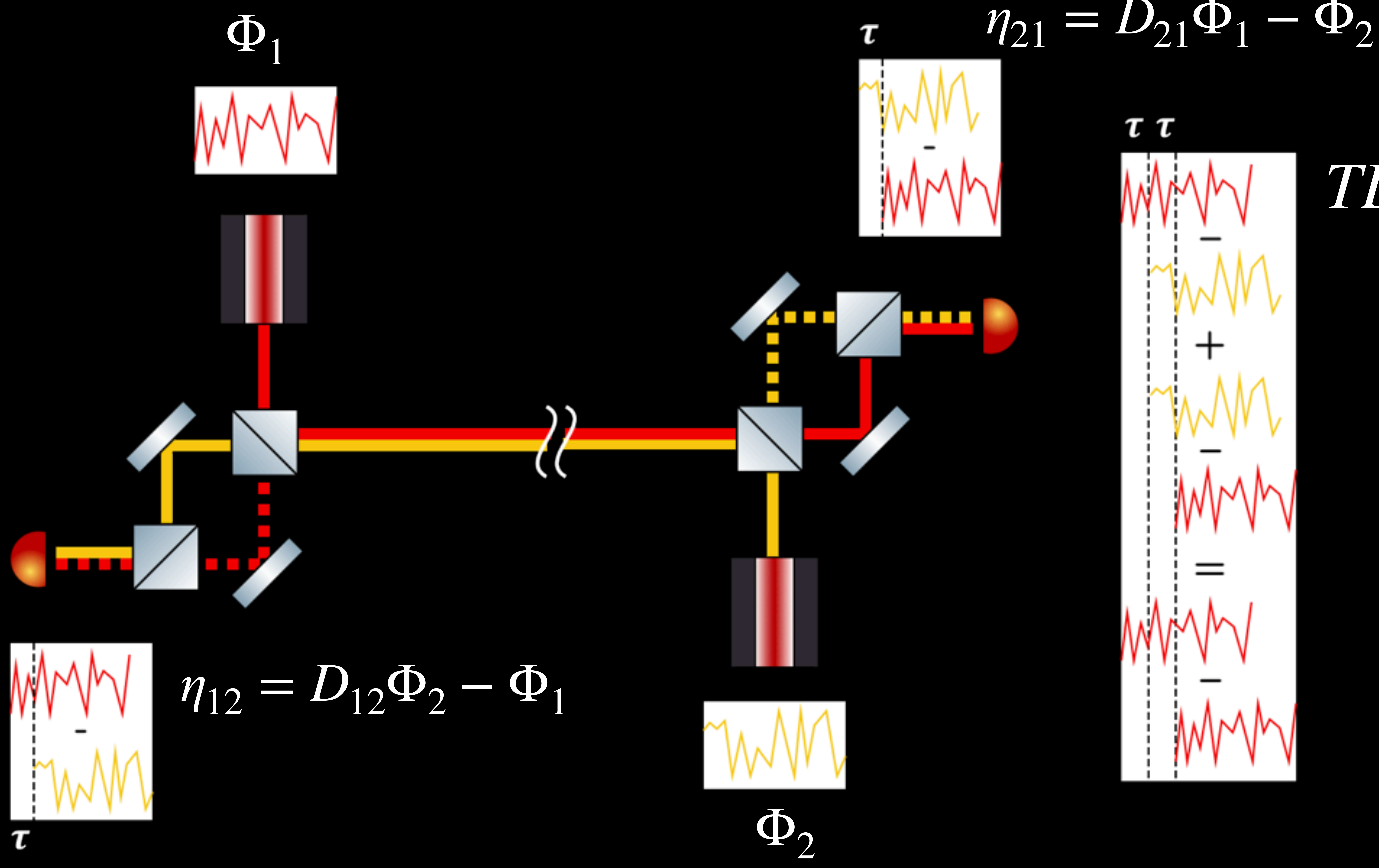


$$\eta_{12} = D_{12}\Phi_2 - \Phi_1$$



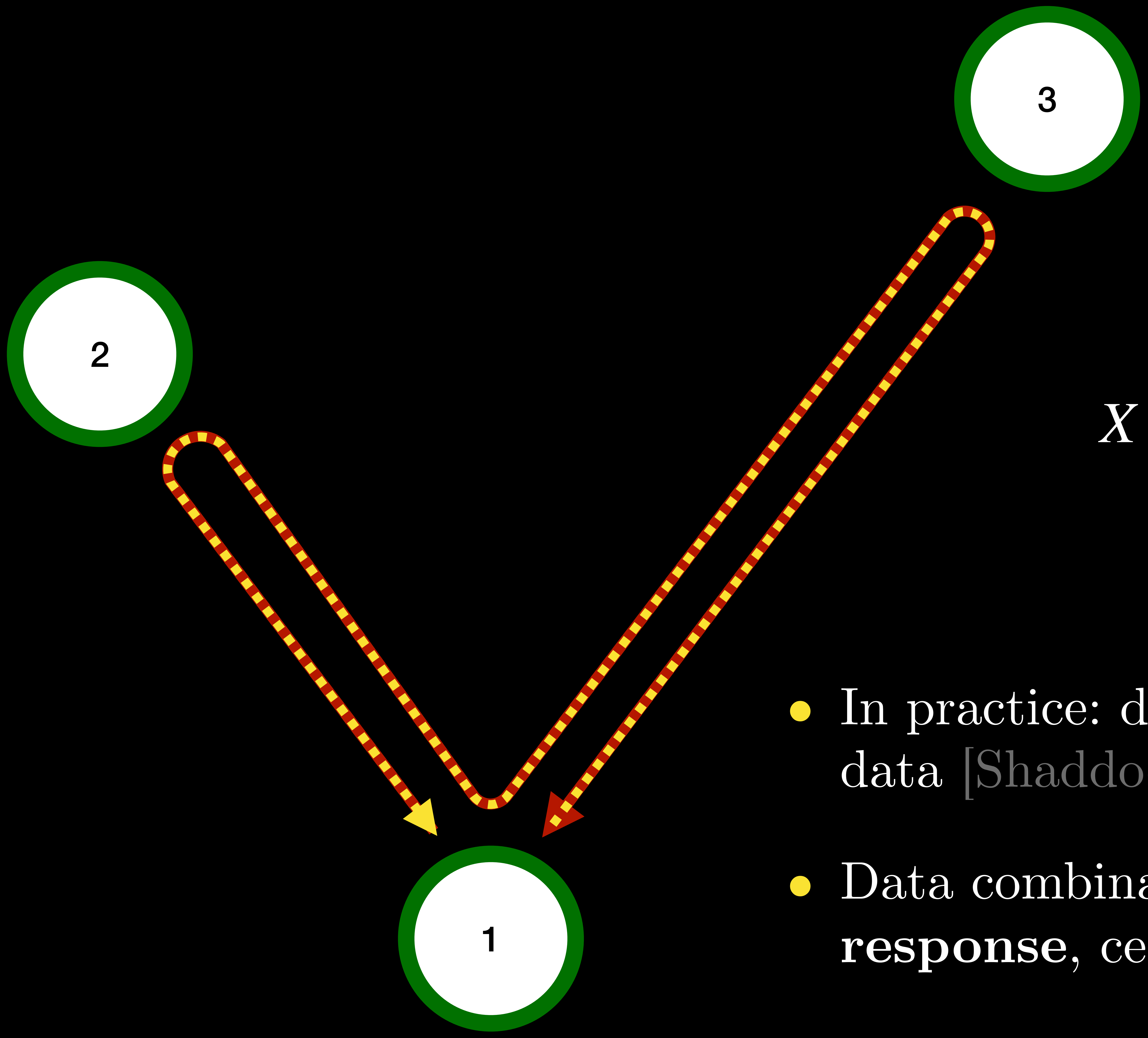
$$\Phi_1(t_e) \equiv D_{21}\Phi_1(t_r)$$
$$= \Phi_1(t_r - d_{21}(t_r))$$

TDI toy model



$$TDI = \eta_{12} + \mathbf{D}_{12}\eta_{21}$$
$$= \mathbf{D}_{12}\Phi_2 - \Phi_1$$
$$+\mathbf{D}_{12}(\mathbf{D}_{21}\Phi_1 - \Phi_2)$$
$$= \mathbf{D}_{121}\Phi_1 - \Phi_1$$

Full first generation TDI

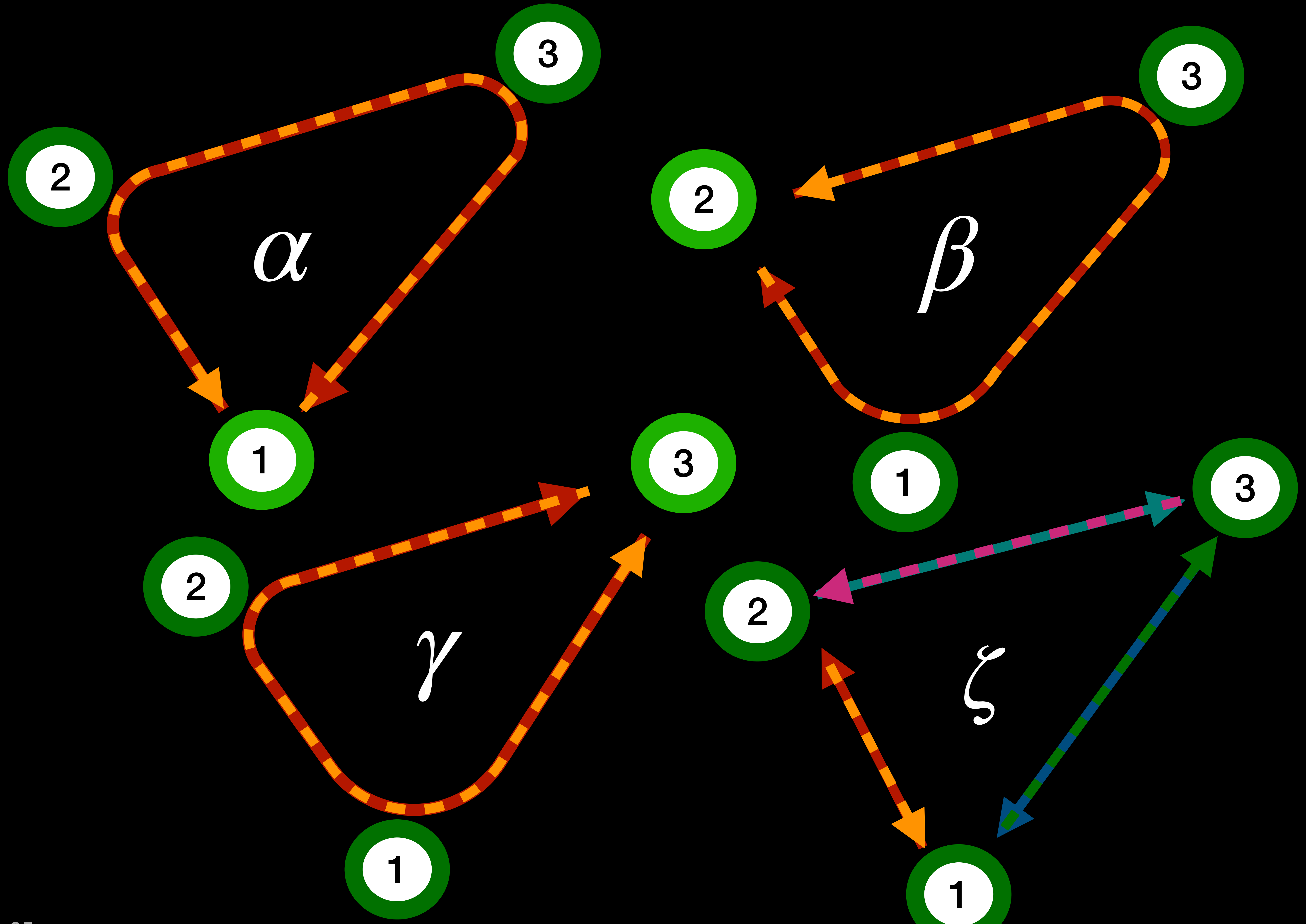


$$X = \eta_{12} + D_{12}\eta_{21} + D_{121}\eta_{13} + D_{1213}\eta_{31}$$
$$-\eta_{12} - D_{13}\eta_{31} - D_{131}\eta_{13} - D_{1312}\eta_{21}$$
$$= (D_{12131} - D_{13121})\Phi_1$$

- 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?

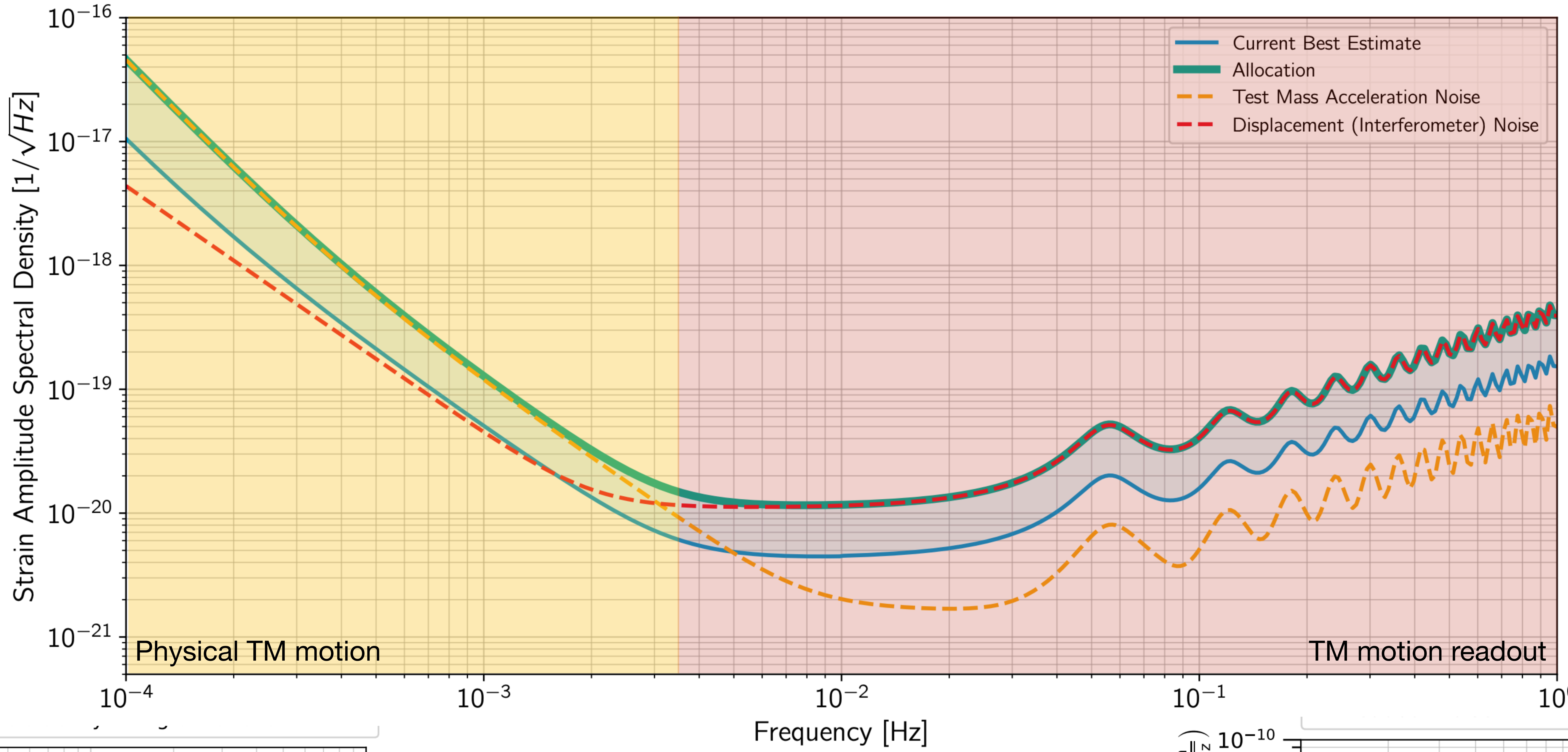
- For a static constellation, all TDI variables can be build from 4 generators [Dhurandhar et al., 2002]
- Only three independent: $(1 - D_{12}D_{23}D_{31})\zeta = (D_{23} - D_{31}D_{12})\alpha + (D_{31} - D_{12}D_{23})\beta + (D_{12} - D_{23}D_{31})\gamma$

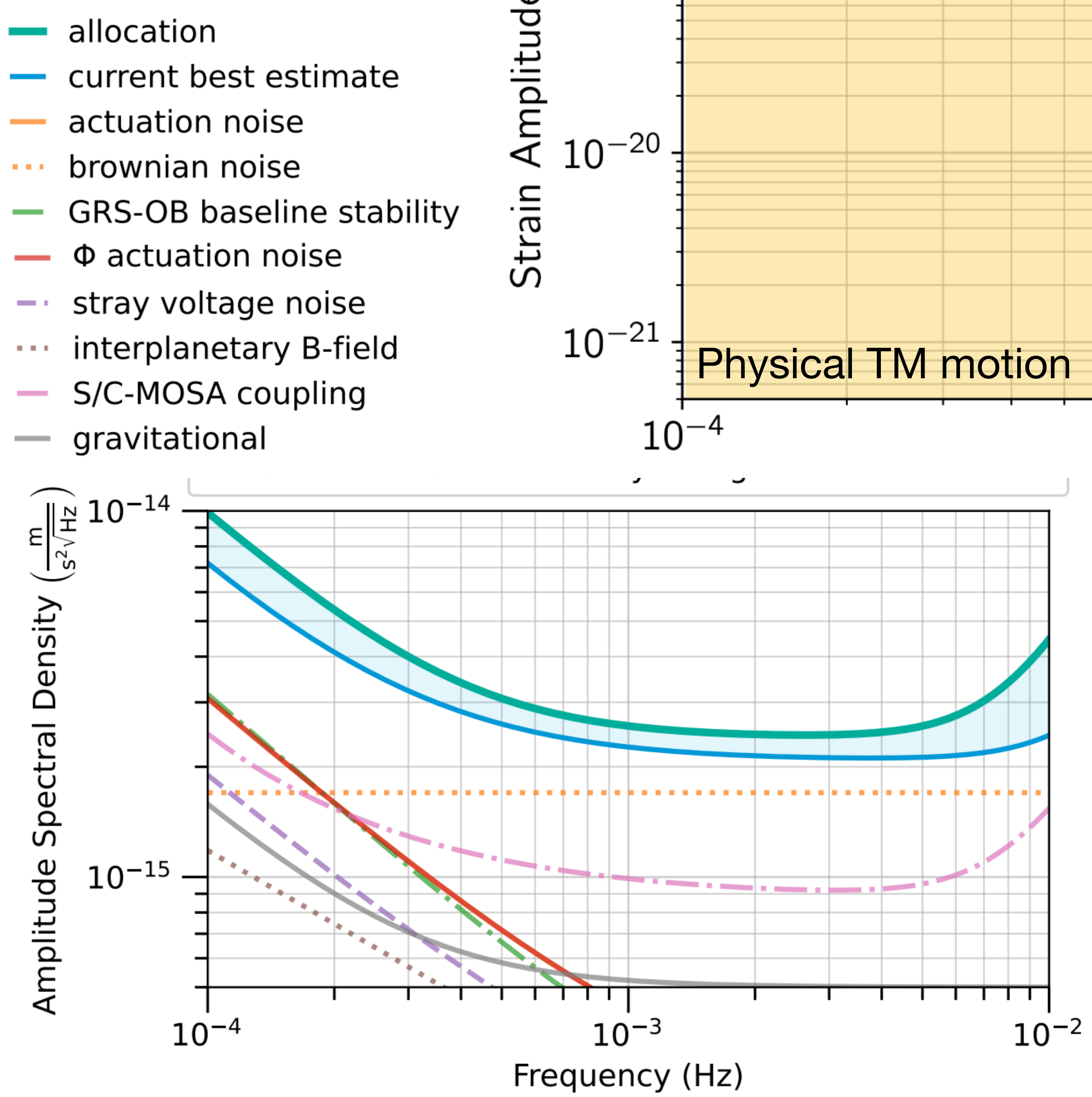


- In 'good' (?) approximation:
  - Only 3 channels independent even in realistic scenarios (time-varying orbits)
  - Popular choice: 3 Michelson combinations (X_2, Y_2, Z_2)
  - Under (strong) assumptions: easy to construct noise- and signal orthogonal (A, E, T)
  - At low frequency: only A,E sensitive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

LISA Performance and Sensitivity

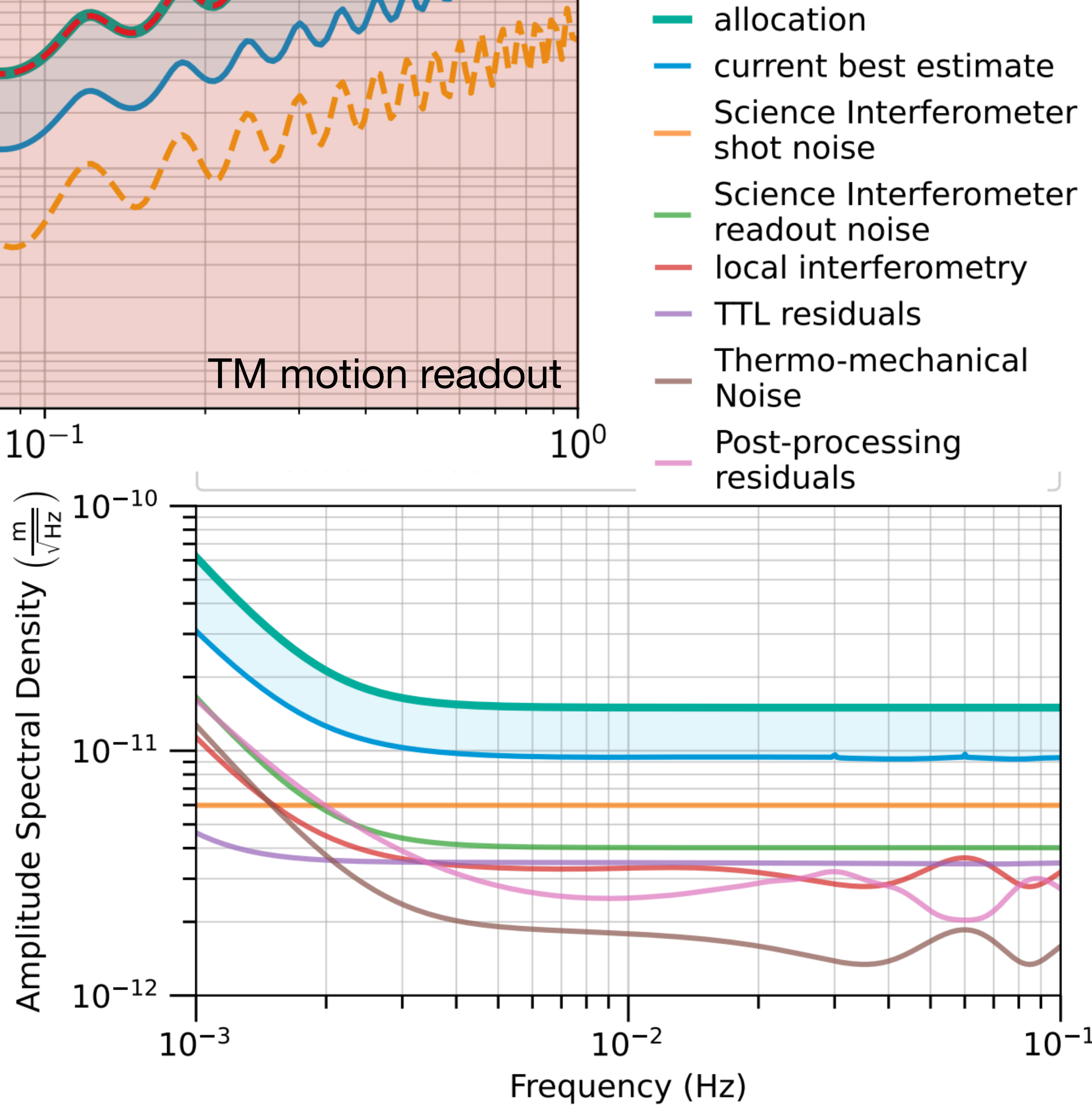
Main limiting noise sources left after TDI



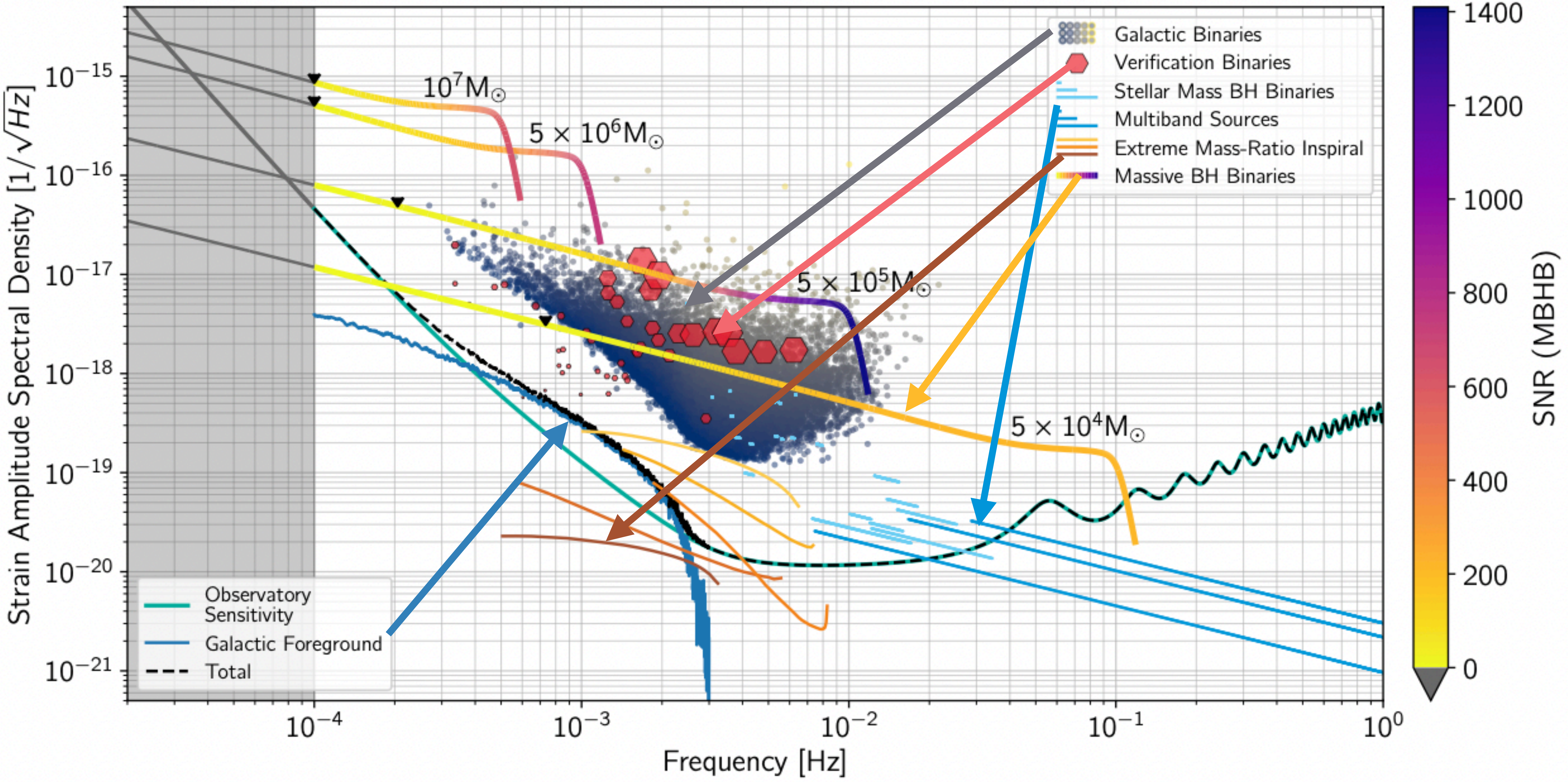


$$S_h(f) \approx \frac{T^X_{acc} S^X_{acc} + T^X_{oms} S^X_{oms}}{2\, R^X_{GW}}$$

!!!



LISA Sensitivity vs. science objectives



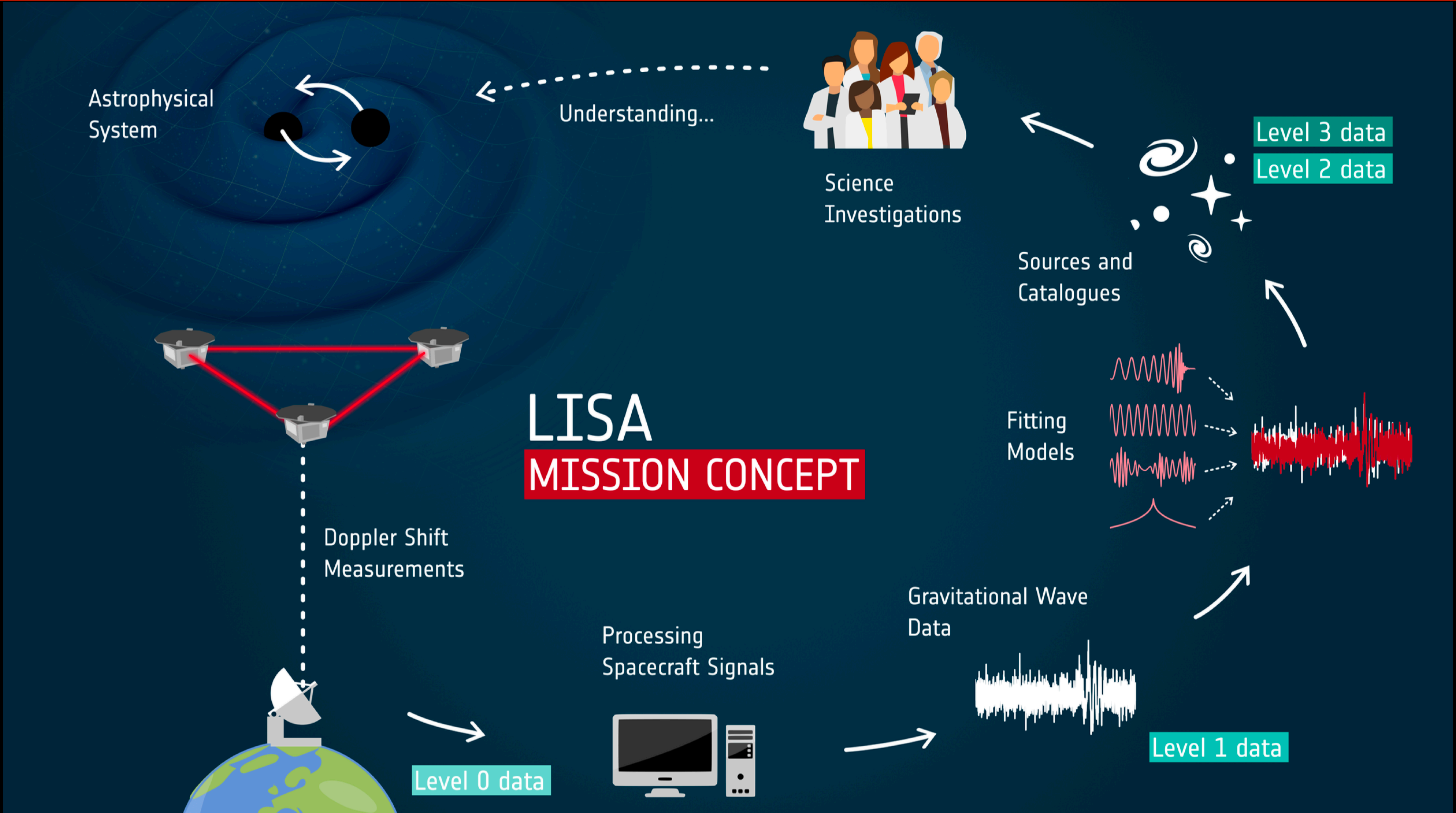
LISA Sensitivity vs. science objectives

With great power come great data analysis challenges...

Example, LDC Sangria: galactic binaries, MBHBs, instrumental noise

- 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 exists, 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



Thank you for your attention!