LISA

Laser Interferometer Space Antenna

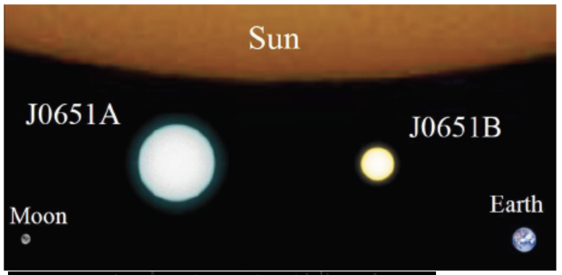
LISA - Simulation & L0-L1 data processing WGs

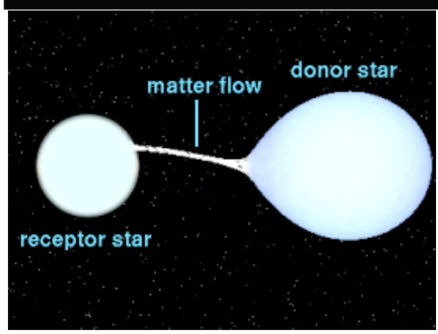
Sweta Shah

Albert Einstein Institute, Hannover

Max Planck Institute for Gravitational Physics

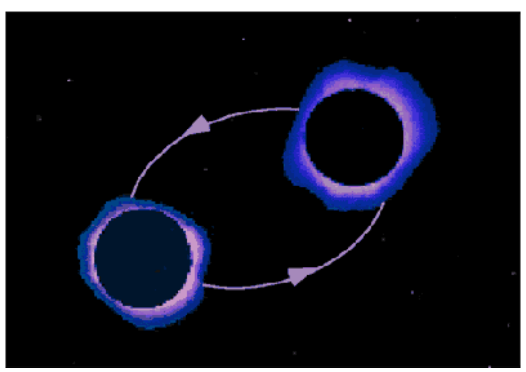
LISA Science is rich



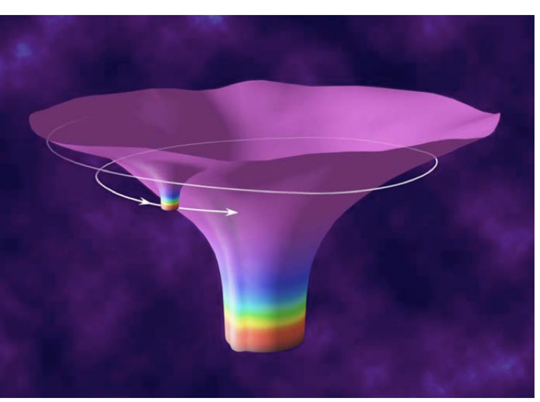


GBs

EM ~ 50
GW~30,000



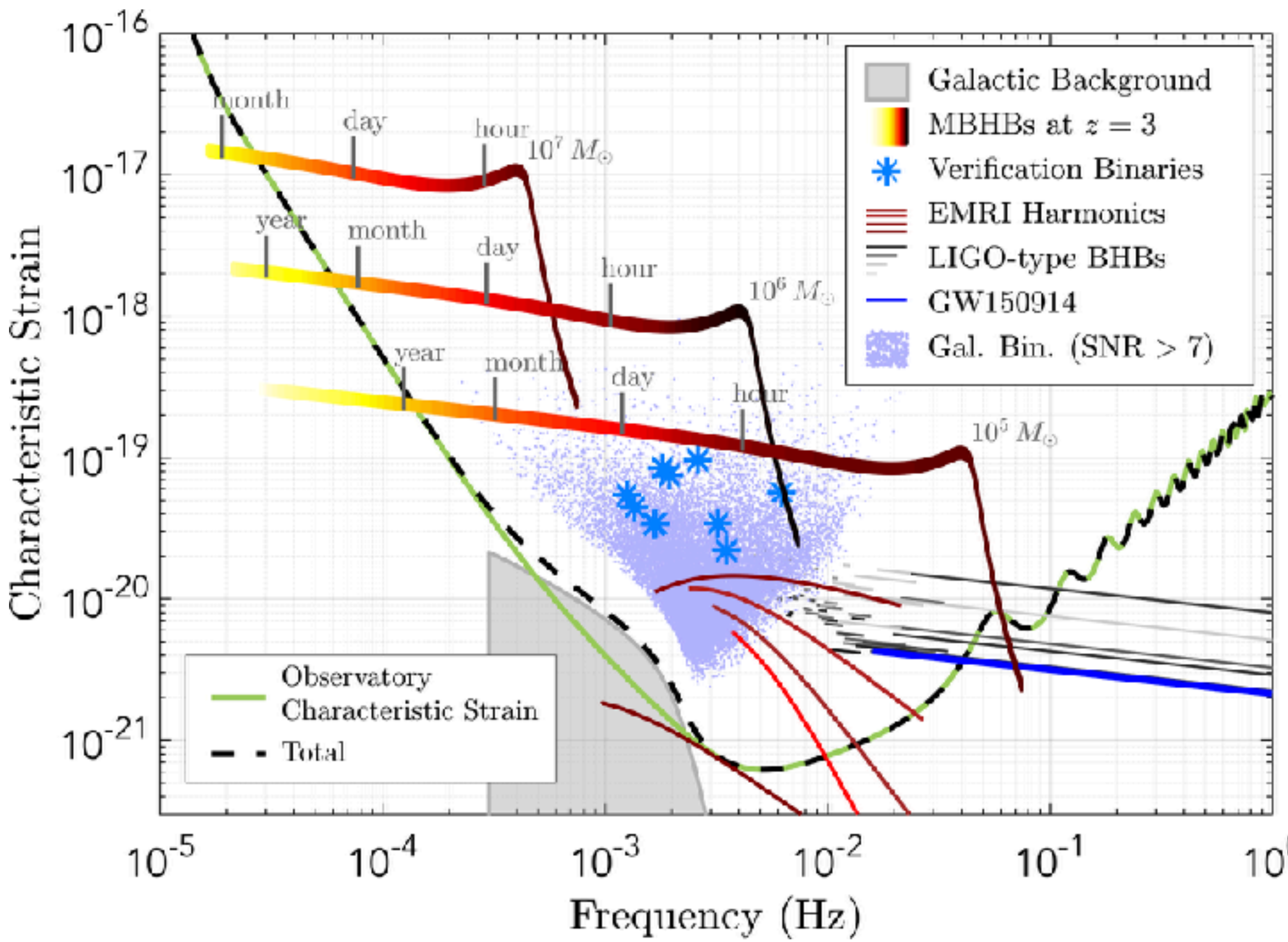
MBHs



EMRIs

Figs: The Gravitational Universe 2013

Sensitive to low-f GWs



Verification binaries ~14
Kupfer, Korol, Shah et al. 2018

Figure: LISA L3 Proposal

Simulation and INReP WGs

L0

Hosted in in2p3 gitlab

- T-1 LISANode Release and Repository Management
- T-2 LISANode Requirements Specifications
- T-3 LISANode Optimization
- T-4 LISANode Interfaces Development
- T-5 Implementation of TM, SC and MOSA Dynamics
- T-6 Implementation of Tilt-to-Length
- T-7 Implementation of Laser Locking Scheme and Frequency Plan
- T-8 Implementation of Clock Noise
- T-9 Implementation of Relativistic Effects
- T-10 Noise models management
- T-11 Instrumental artefacts

Jean-Baptiste Bayle, Olaf Hartwig + developers

Chairs: Luigi Ferraioli, Joseph Martino, Daniele Vertugno

L1

PyTDI
Project ID: 9878

INREP Framework
Project ID: 9951

INREP_proto
Project ID: 9901

LISA Models
Project ID: 12389

Kalman4SpaceIfo
Project ID: 9864

- TLT 1 Project Planning
- TLT 2 L0-L1 Requirement Doc
- TLT 3 Analytical Formulation for performance model
- TLT 4 Notations & Conventions
- TLT 5 Physical Units
- TLT 6 Astrophysical Dataset
- **TLT 7 Phase A Reference Pipeline: INReP**
- TLT 8 Test & Verification

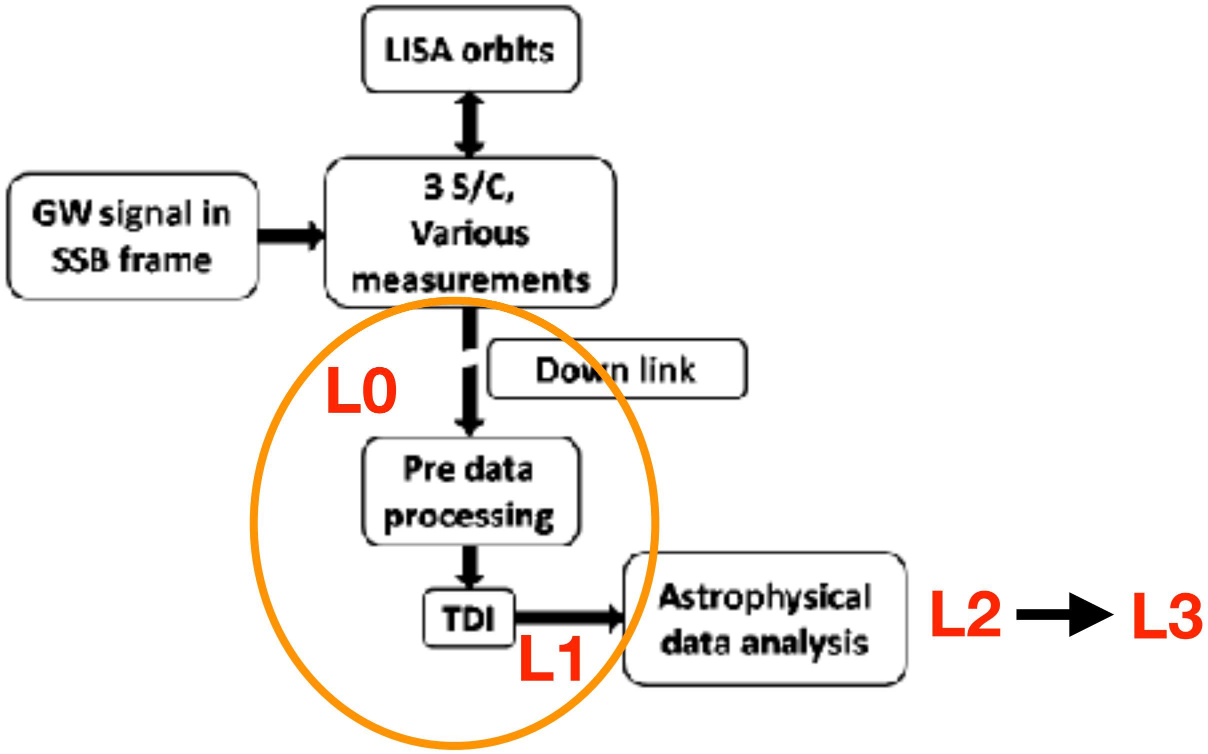
More: Sampling and Filter tests, etc.

Scrum Team: Karsten Wiesner, Niklas Reinhardt, Martin Staab, Olaf, Hartwig, Jean-Baptiste Bayle, Jakob Livschitz, Fabian Euchner, Tim Haase, Uwe Lammers, Sweta Shah

Chairs: Sweta Shah, Yves Lemiere

LISA Data chain : L0 —> L1

LDPG - Working Group 6 - INReP
Initial Noise Reduction Pipeline



Yan Wang, PhD thesis 2014

must satisfy
L0-L1
Requirements

INReP

Raw data (Ifo measurements + auxilliary)
L0

→ Pre-processing (Kalman Filter) OR another scheme

→ TDI processing

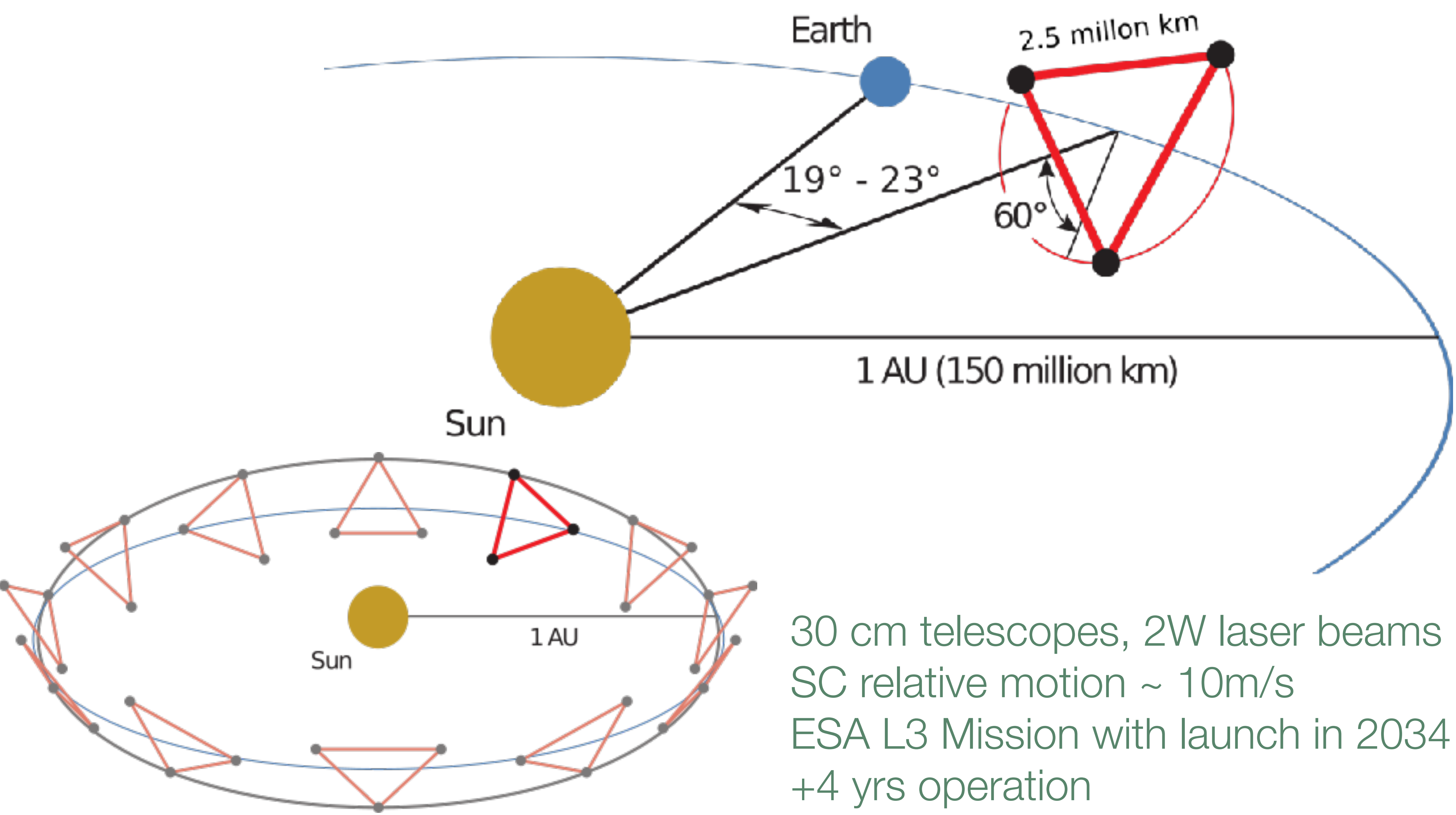
Suppressions of:
laser + OB noise
clock noise
tilt-to-length
Relative intensity noise
Back-link fibre
Etc.

→ **L1**

TDI data streams (Michelson, Sagnac …)

L1 in different temporal **releases** (as KF improves data quality with increasing incoming data)

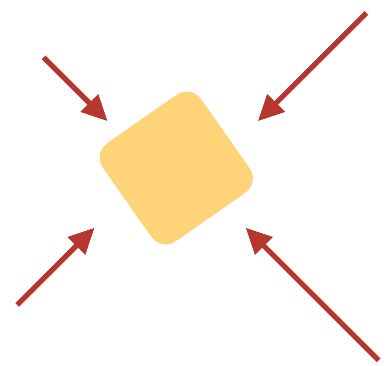
LISA Constellation



30 cm telescopes, 2W laser beams
SC relative motion ~ 10m/s
ESA L3 Mission with launch in 2034
+4 yrs operation

Engineering Requirements

Freely falling test mass (TM)



Residual acceleration noise

$$S_g^{1/2} < 3\,\mathrm{fm/s^2/Hz^{1/2}} \times \left[1+\left(\frac{0.4\,\mathrm{mHz}}{f}\right)^2\right]^{1/2}$$

Interferometric sensing noise

$$S_{\mathrm{link}}^{1/2} < 10\,\mathrm{pm/Hz^{1/2}} \times \left[1+\left(\frac{2\,\mathrm{mHz}}{f}\right)^4\right]^{1/2}$$

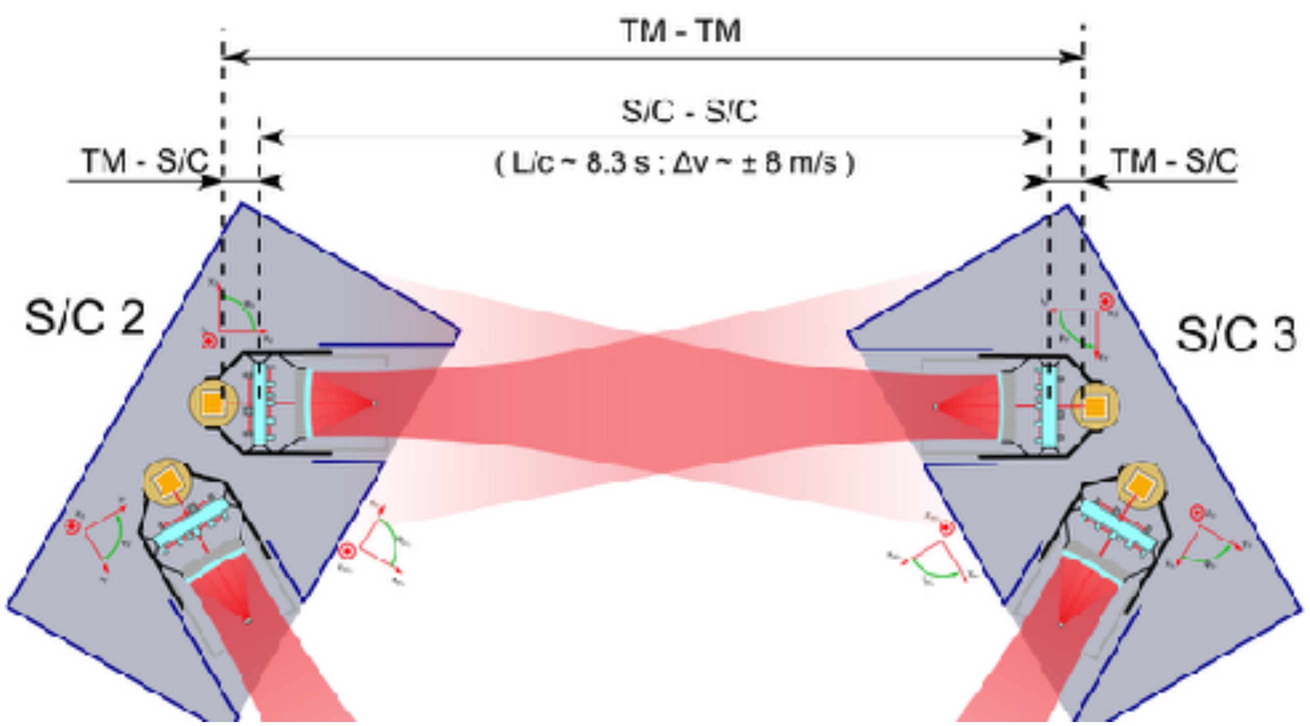
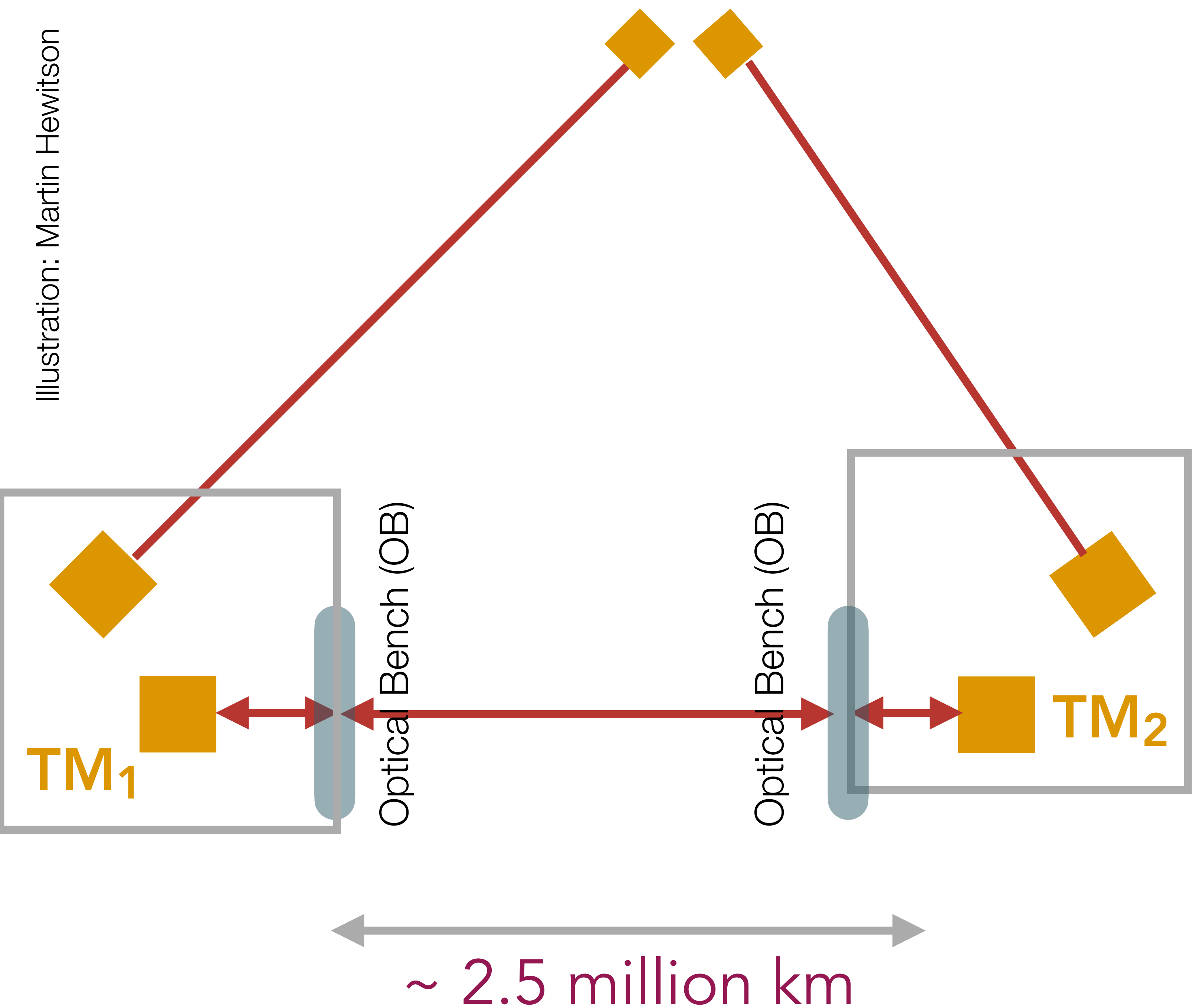


Figure 2 Payload Document Description

Measurement Principle

Illustration: Martin Hewitson



Split Interferometry:

1. TM to OB
2. OB to OB
3. OB to TM

Heterodyne Interferometry

Transponder mode

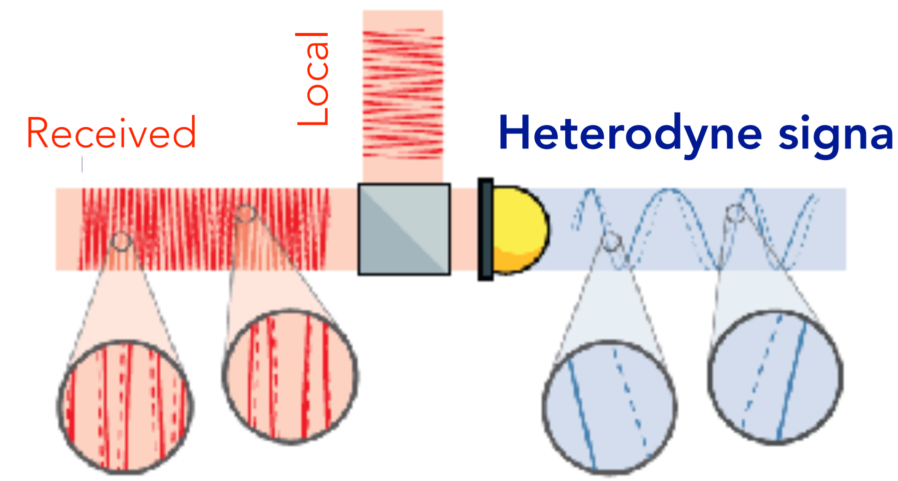
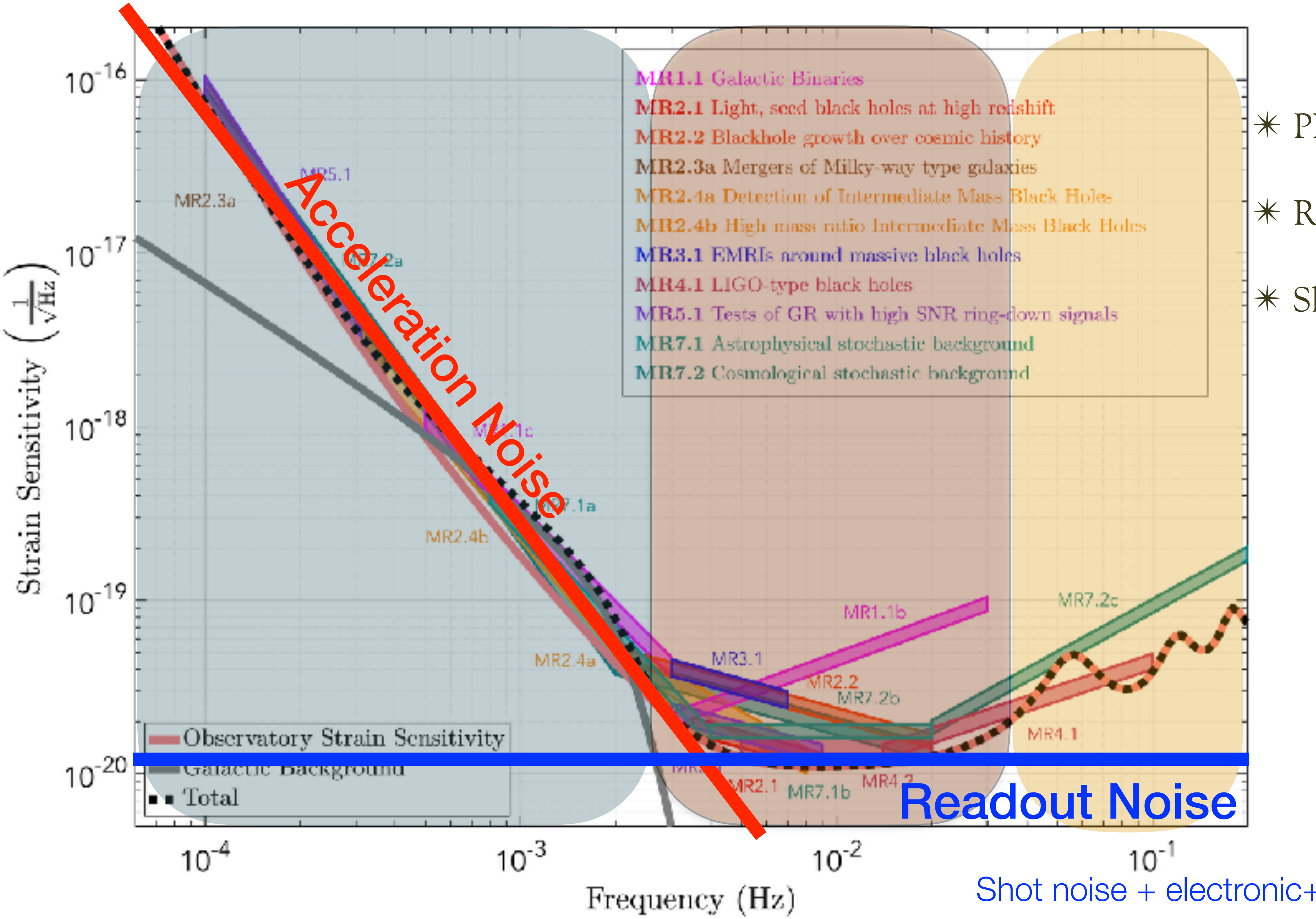


Figure: Simon Barke PhD thesis 2015

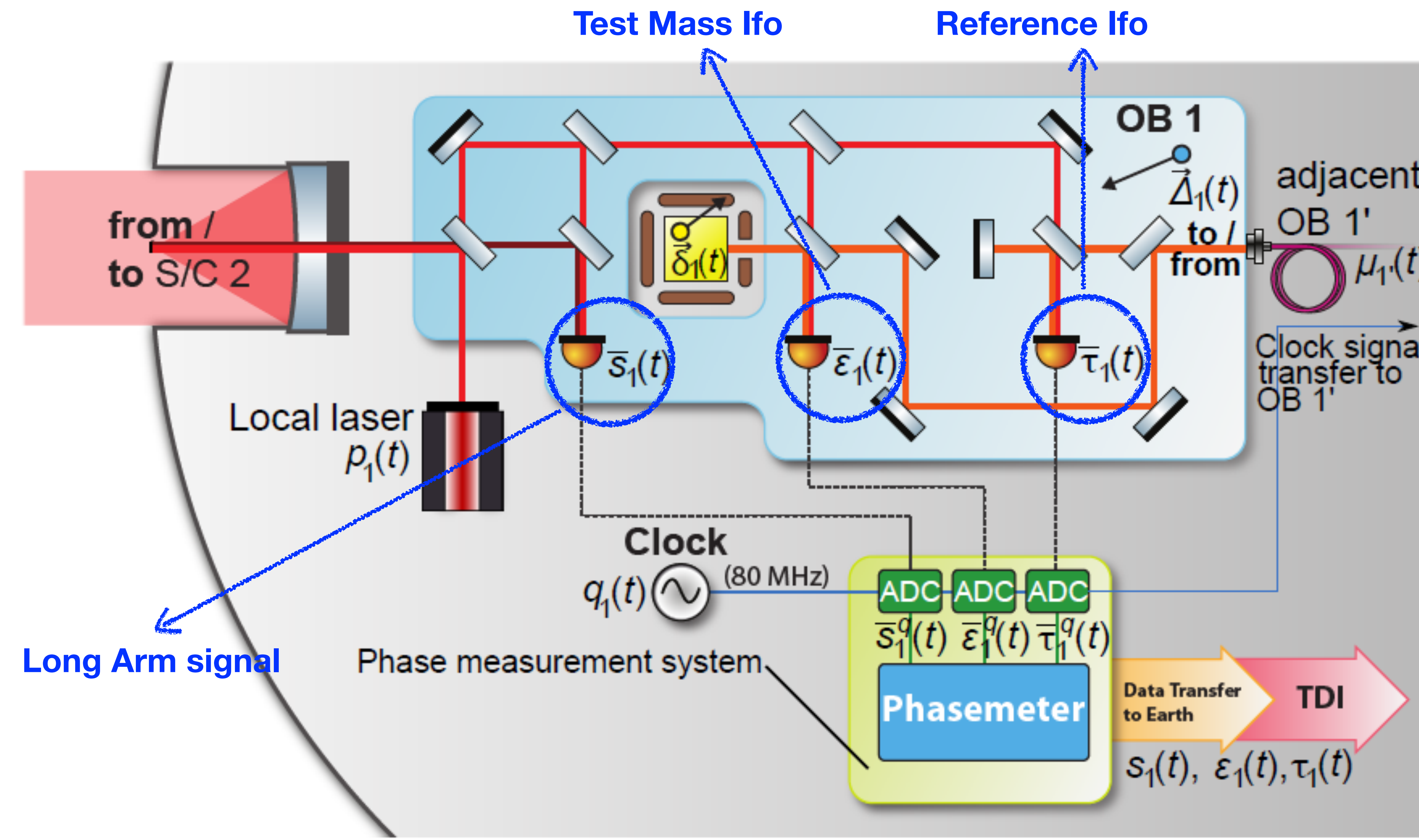
Noise Floor



- PM noise -> at low f
- Readout noise -> at mid f
- Short GWs -> at high f

Figure: LISA L3 Proposal

Raw data - L0



Markus Otto, PhD thesis 2014

LISA L0 Simulation

- LISANode - python graph based, atomic nodes in C++
- Laser beam frequency - offsets & fluctuations

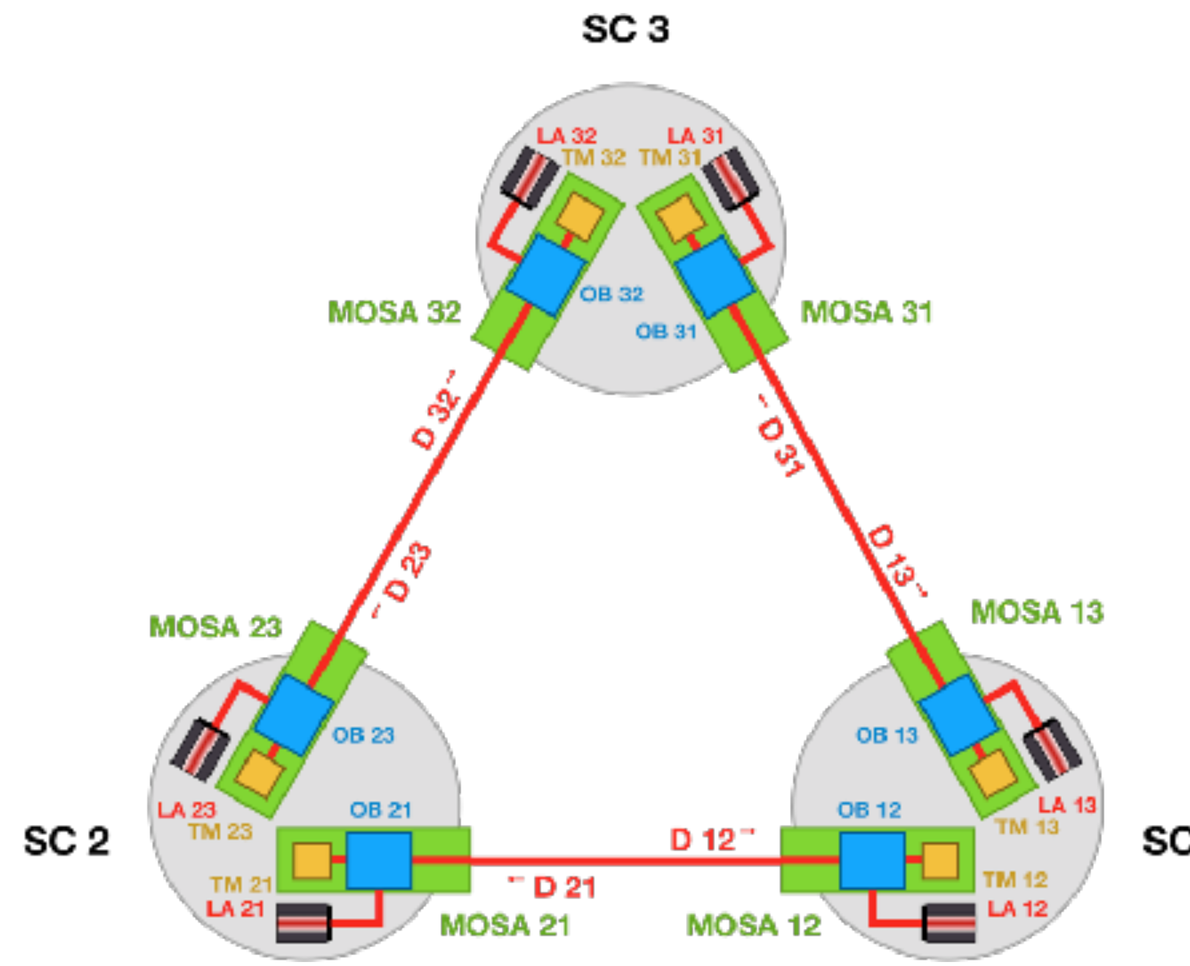
$$E(\tau) = E_0(\tau)\cos(2\pi\Phi(\tau))$$

$$\nu(\tau) = \nu_0 + \nu^o(\tau) + \nu^\epsilon(\tau)$$

- Modulations: sidebands, clock tone

$$\mathrm{E}(\tau) = E_0 e^{j2\pi(\Phi_c(\tau)+m\Phi_m(\tau))}$$

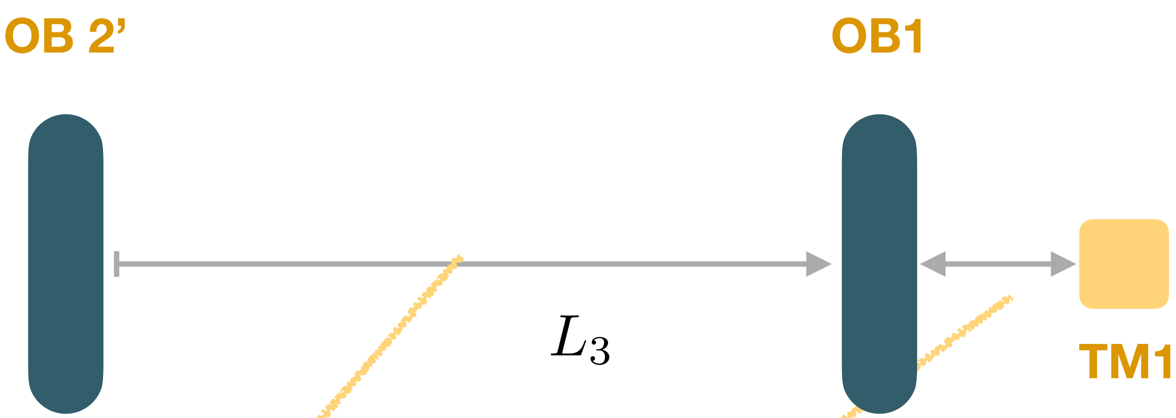
- Beam propagation - SC proper time, propagated signals by proper pseudo-range (light travel time + proper time conversion)

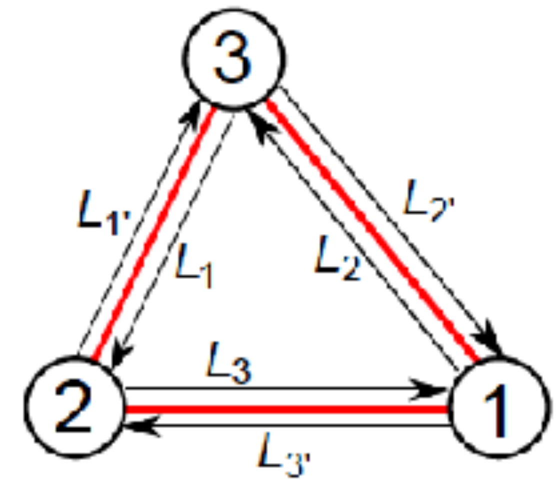


LISA Convention and Notation
Ref: Eg. arXiv 2103.06976

LISA Simulation Model Technical Note
Bayle & Hartwig

L0: Observation Equations





Markus Otto, PhD thesis 2014

Long Arm signal $s_1(t) = H_1 + p_{2':3} - p_1 + \left(\frac{2\pi}{\lambda_{2'}}\right)\left(-\vec{n_3}\cdot\vec{\Delta_{2':3}} - \vec{n_{3'}}\cdot\vec{\Delta_1}\right)$

GW — Laser noise — OB motion

Test Mass Ifo $\varepsilon_1(t) = p_{1'} - p_1 + \left(\frac{2\pi}{\lambda_{1'}}\right)\left[2\left(-\vec{n_{3'}}\cdot\vec{\delta_1} + \vec{n_{3'}}\cdot\vec{\Delta_1}\right) + \mu_{1'}\right]$

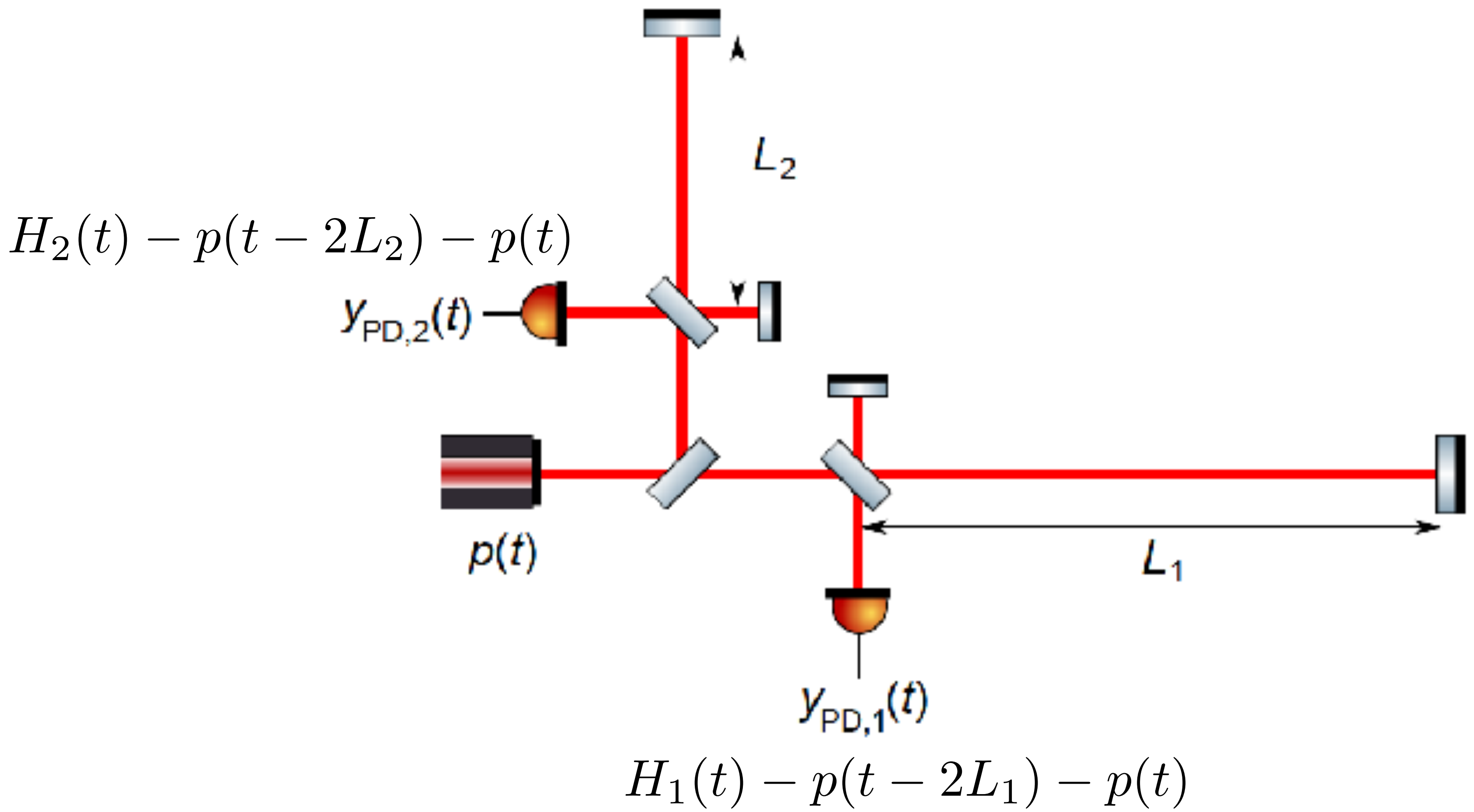
Laser noise — TM motion

Reference Ifo $\tau(t) = p_{1'} - p_1 + \mu_{1'}$

mm		nm		pm
Laser noise equiv. Strain	$\gg$	OB motion Strain	$\gg$	GW Strain

L1 Time Delay Interferometry

Unequal Arm Michelson Ifo



$$x := y_{\mathrm{PD},1}(t - 2L_2) - y_{\mathrm{PD},2}(t - 2L_1) - [y_{\mathrm{PD},1}(t) - y_{\mathrm{PD},2}(t)]$$

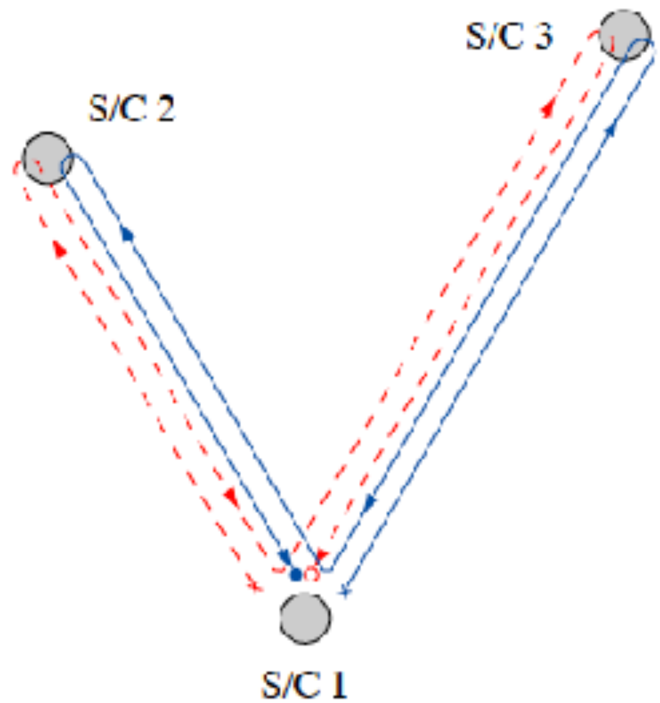
Giamperi, Hellings, Tinto & Faller, Opt. Comm. 123, 1996
Tinto & Armstrong, PRD 59, 1999
Figure from M. Otto Thesis 2014

L1 Time Delay Interferometry

Arms unequal
by 1% ~
20000 km

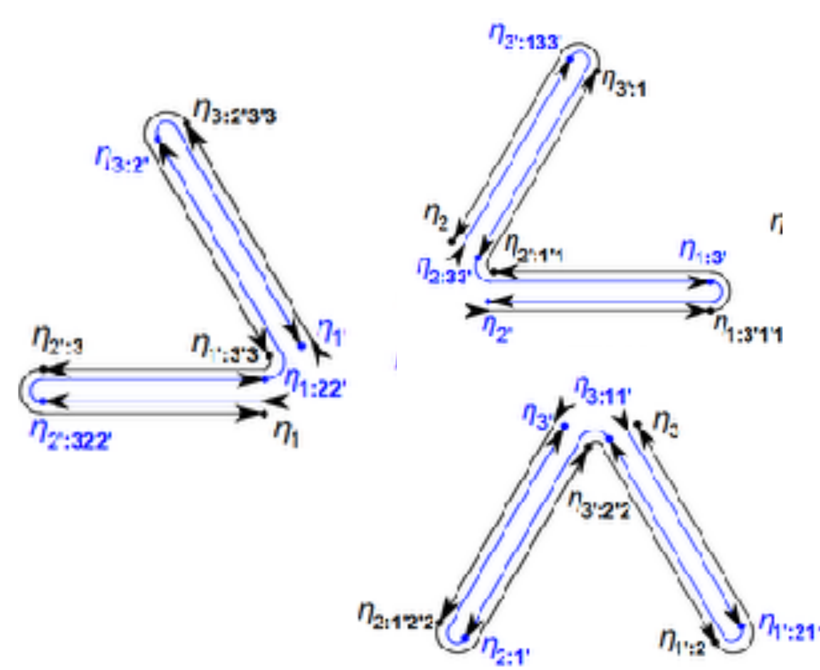
$$L_1 \neq L_2 \neq L_3$$

Fig:Shaddock et al 2003



$$X = [(s_{31} + s_{13,2}) + (s_{21} + s_{12,3'})_{,22'}] - [(s_{21} + s_{12,3'}) + (s_{31} + s_{13,2})_{,33'}]$$

3 Independent
noise-free signals



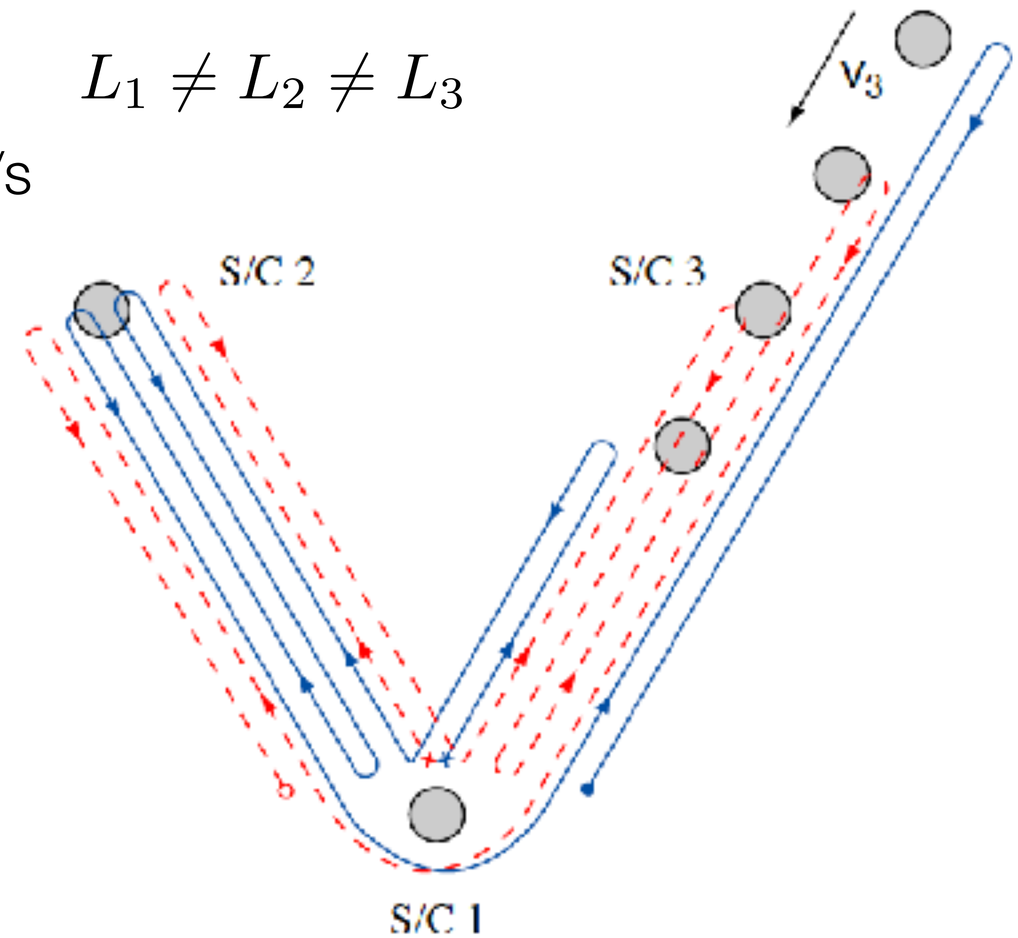
Lot of work has been done and continuing:
Armstrong et al,
Otto et al,
Vinet et al,
Dhurandhar

L1 Time Delay Interferometry

Fig:Shaddock et al 2003

Unequal & time
varying arm @ 10m/s

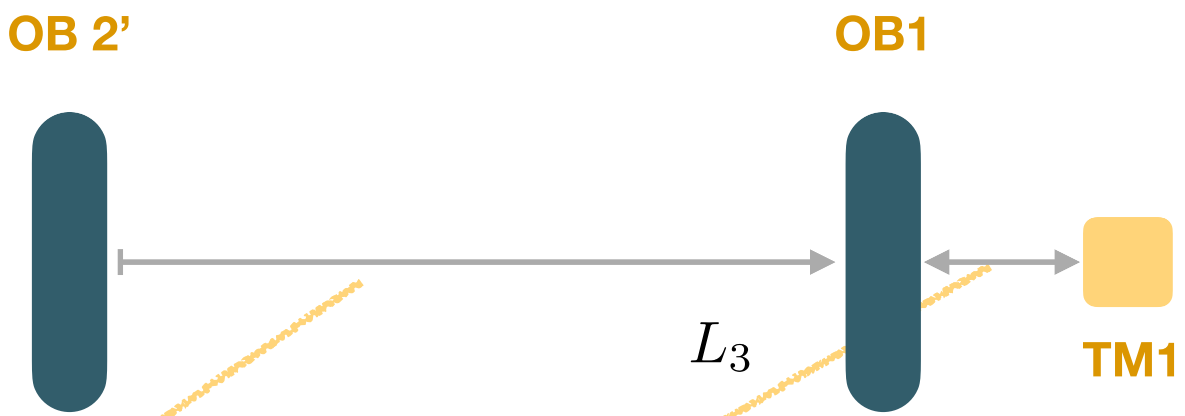
$$L_1 \neq L_2 \neq L_3$$



$$\begin{aligned} X_1 = [& (s_{31} + s_{13;2}) + (s_{21} + s_{12;3'})_{;2'2} + (s_{21} + s_{12;3'})_{;33'2'2} \\ & + (s_{31} + s_{13;2})_{;33'33'2'2}] - [(s_{21} + s_{12;3'}) \\ & + (s_{31} + s_{13;2})_{;33'} + (s_{31} + s_{13;2})_{2'233'} + (s_{21} \\ & + s_{12;3'})_{;2'22'233'}] + \frac{1}{2} [(\tau_{21} - \tau_{31}) - (\tau_{21} - \tau_{31})_{;33'} \\ & - (\tau_{21} - \tau_{31})_{;2'2} + (\tau_{21} - \tau_{31})_{;33'33'2'2} \\ & + (\tau_{21} - \tau_{31})_{;2'22'233'} - (\tau_{21} - \tau_{31})_{;2'233'33'2'2}] \end{aligned}$$

Lot of work has been done and continuing:
Armstrong et al,
Otto et al,
Vinet et al,
Dhurandhar

L0: Observation Equations



Secondary Noises

Power $\sim 1/10^8$

Clock $\sim 1/10^{13}$

$$s_1(t) = H_1 + p_{2':3} - p_1 + \left(\frac{2\pi}{\lambda_{2'}}\right)\left(-\vec{n_3}\cdot\vec{\Delta_{2':3}} - \vec{n_{3'}}\cdot\vec{\Delta_1}\right)$$

GW — Laser noise — OB motion

$$\varepsilon_1(t) = p_{1'} - p_1 + \left(\frac{2\pi}{\lambda_{1'}}\right)\left[2\left(-\vec{n_{3'}}\cdot\vec{\delta_1} + \vec{n_{3'}}\cdot\vec{\Delta_1}\right) + \mu_{1'}\right]$$

Laser noise — OB motion

$$+ N^{\mathrm{TTL}}_{\mathrm{SC},\ell oc\&\mathcal{R}} + N^{\mathrm{RIN}} + N^{\mathrm{clockNoise}}$$

$$\tau(t) = p_{1'} - p_1 + \mu_{1'}$$

L0-L1: Pre-processing before TDI

refers to clock in SC2

refers to clock in SC1

$$X(t) = \eta_{2'}\left(\hat{\tau}_2 - \frac{L_3}{c} - \frac{L_2}{c} - \frac{L_{2'}}{c}\right) + \eta_1\left(\hat{\tau}_1 - \frac{L_2}{c} - \frac{L_{2'}}{c}\right) + \ldots$$

delays (meter accuracy)

$\hat{\tau}_1, \hat{\tau}_2$ nanosec timestamping accuracy

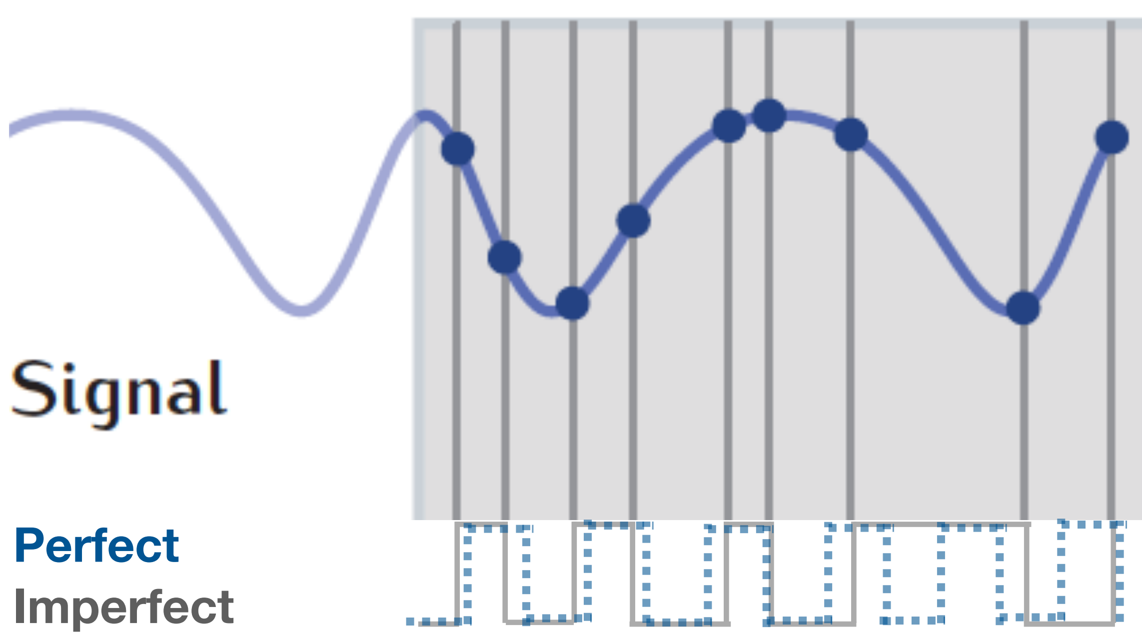


Figure: Adapted from Simon Barke PhD thesis

Long Arm, Test Mass, Reference Signals

Unsynchronized L0 data and unevenly sampled

$$s_i(\hat{\tau}), \epsilon_i(\hat{\tau}), \tau_i(\hat{\tau})$$

Pseudo Random Code (PRN)

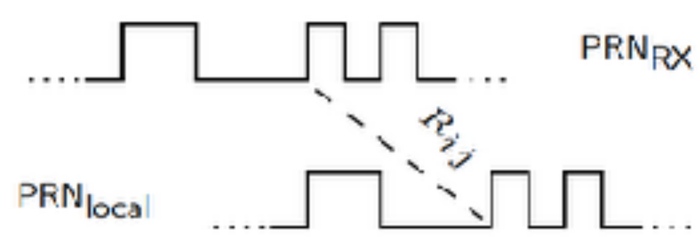


Fig: O. Hartwig

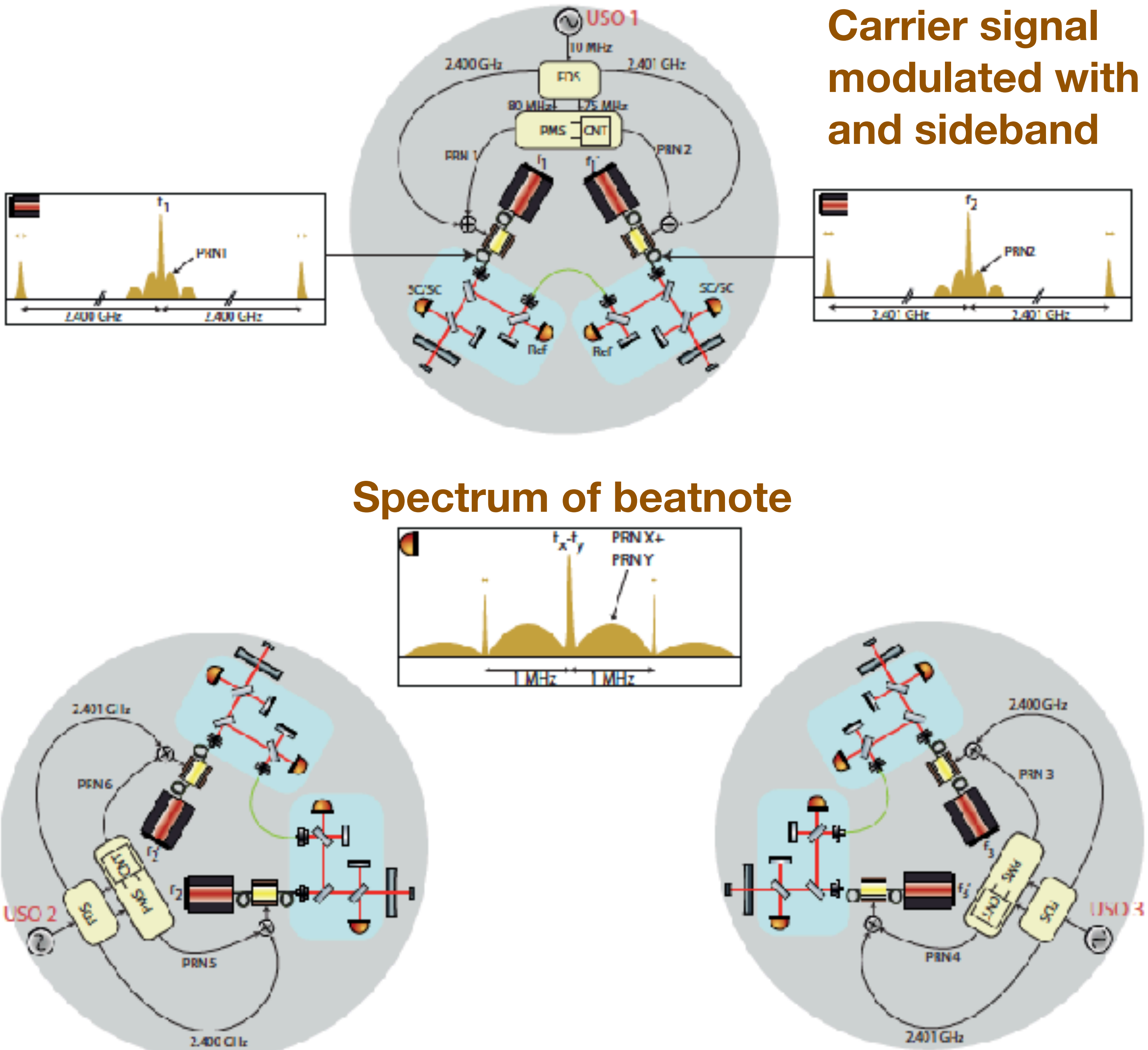
Synchronized L1 data $X(t), Y(t), Z(t)$

L0-L1: Pre-processing before TDI

Clock 1

Carrier signal modulated with PRN and sideband

Spectrum of beatnote

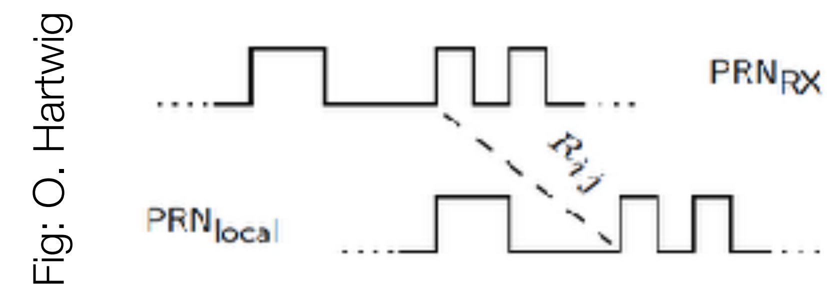


Clock 2

Clock 3

Figure 3 Payload Document Description

Pseudo Random Code (PRN)



Kalman Filter

USOs drift and have biases

Yan Wang et al. PRD 90, 2014
Yan Wang et al. PRD 92, 2015

Clock Synchronization

S/C clock time $\hat{\tau}$ ⟷ S/C proper time, τ ⟷ TCB, t

USO drift + stochastic fluctuations

(Barycentric coordinate frame)

With: Theory & Metrology in SYRTE, Paris

Laser locking schemes

Laser locking schemes necessitated by :

- Doppler shifts ($\pm 10\mathrm{MHz}$) in long arm laser beams
- Bandwidth limitation of photoreceivers and phasemeter: $5 - 25\mathrm{MHz}$
- 6 Lasers
- Give 9 different beatnote frequencies
- Solution: 1 **main/master**, 5 **transponders** with offset phase locking

There are 6 configurations IF one is chosen as main. Use computational geometry to find suitable offset frequencies

Simon Barke 2015, Gerhard Heinzel, fplan, 2018

Tilt to Length in LISA

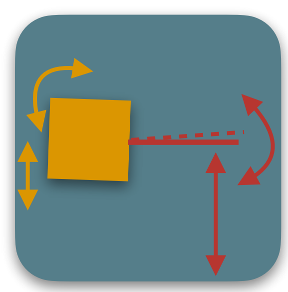
Source is any Misalignment
~91 Misalignments per MOSA

$$\delta s_{\mathrm{IFO}} = c_{\mathrm{IFO},\phi}\left[\Phi_{\mathrm{comp1}} + \Phi_{\mathrm{comp2}} + \ldots\right]$$

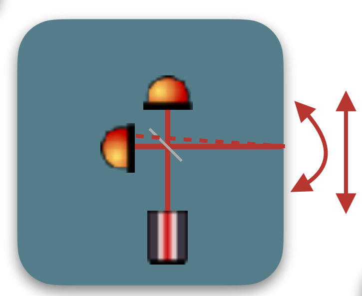
pathlength — Coupling coefficient — Individual components

Assumptions

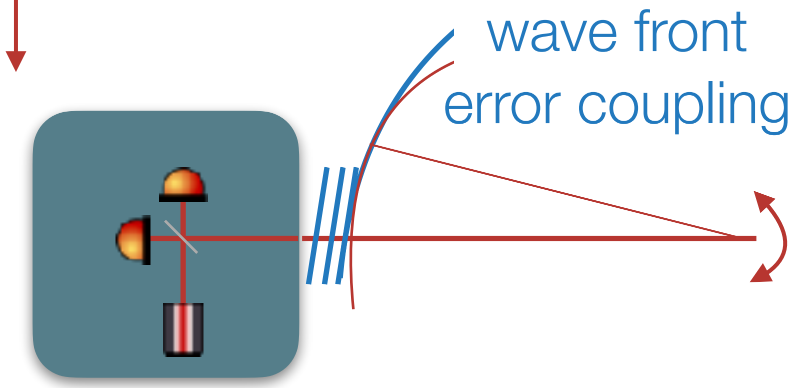
1. TM-Ifo: TM and S/C jitter coupling



2. In Long Arm-Ifo due to local S/C jitter



3. In Long Arm-Ifo due to remote S/C jitter



With:
Gudrun Wanner, Gerhard Heinzel (AEI Hannover)
Ewan Fitzimons (UKATC, UK)

Clock noise in TDI

$$s_1^c(t) = \mathrm{GW} + \mathrm{laser} + \mathrm{OB} + a_1 q_1$$

$$s_1^{sb}(t) = \mathrm{GW} + \mathrm{laser} + \mathrm{OB} + m_{2'} q_{2:3} - m_1 q_1 - c_1 q_1$$

Need additional information

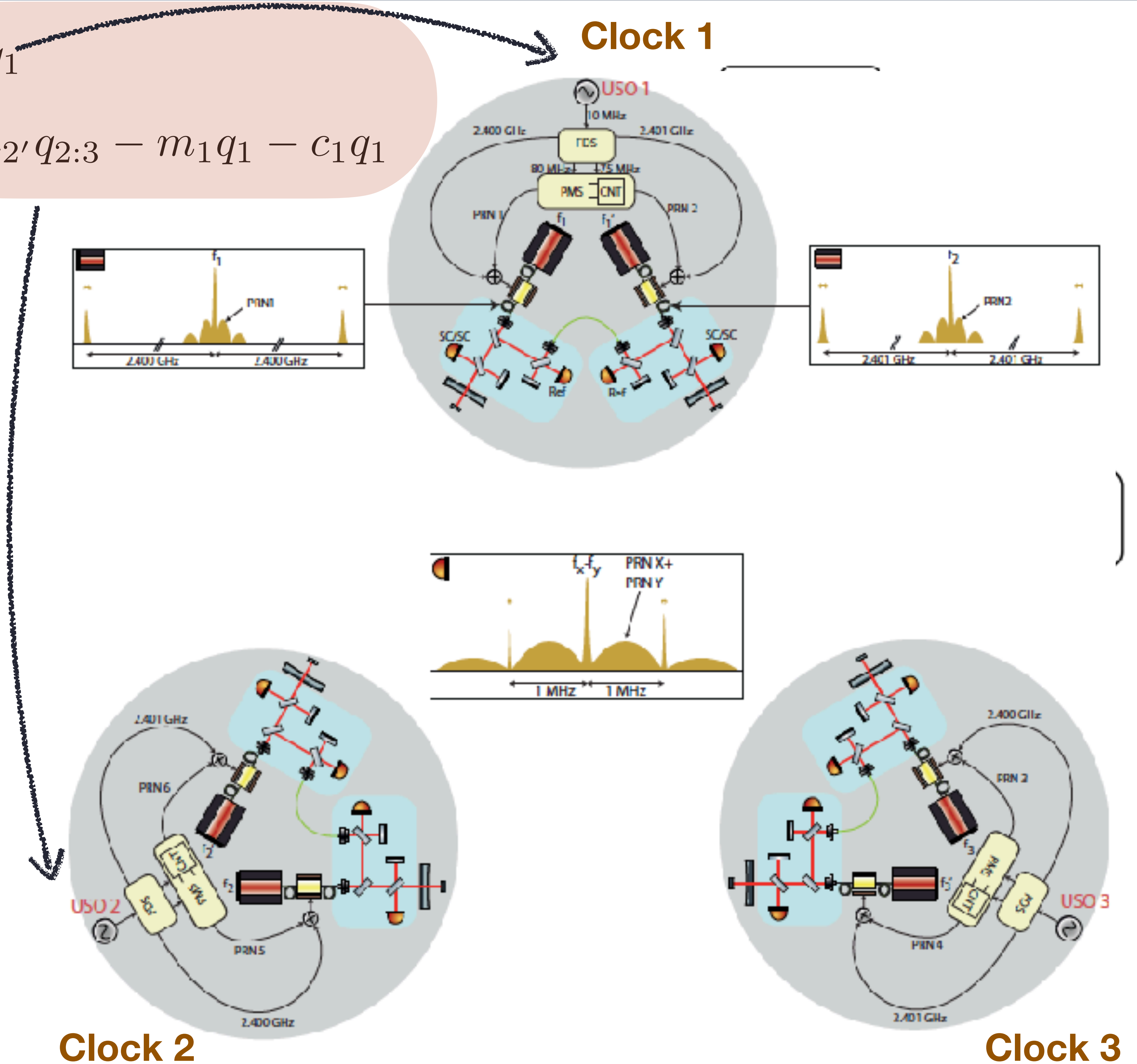


Figure 3 Payload Document Description

Hellings et al. Opt Comm 124 1996
Hellings PRD 64, 2001
Tinto et al. PRD 65, 2002
Otto et al. CQG 29, 2018
Tinto & Hartwig PRD 98, 2018
Hartwig & Bayle, 2020

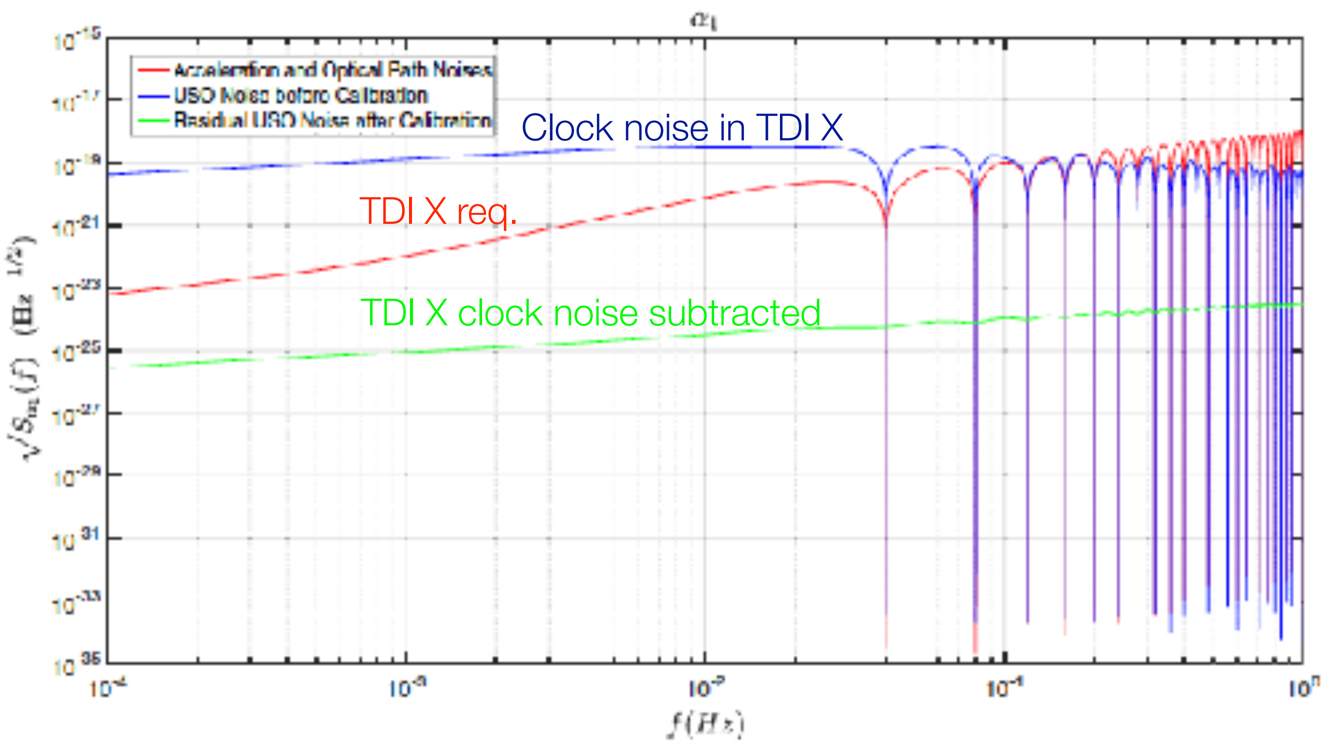
Clock noise - calibration

Assume: USO frequency stability 10^{-13}

Noises: Random processes from lasers, USOs

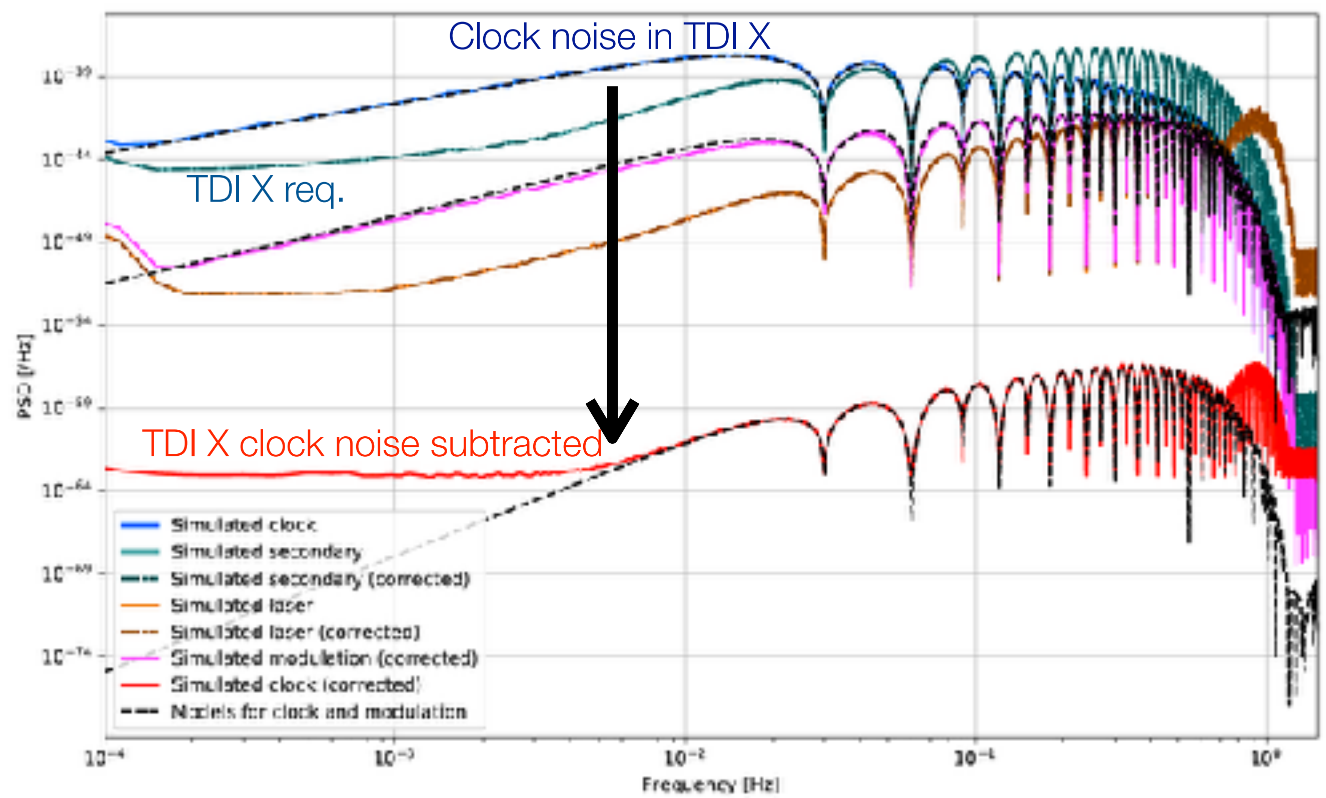
Given: 24 OB measurements

ASD of TDI alpha observable, Analytical



Tinto & Hartwig, PRD98, 2018

PSD of TDI Michelson observable, Numerical LISANode



Hartwig & Bayle, arXiv 2005.02430

Summary & Outlook

- **Ongoing studies** to better understand effects
  - Synchronization
  - Glitches
  - Various orders of algorithms in INREP
  - Frequency planning effect
  - Secondary noise echoes in TDI
  - …

LISA

Laser Interferometer Space Antenna

Thank You!

lisa

L0 —> L1

TM Simulation

LDPG - Simulation Working Group

First Processing

LDPG - INReP

- Verification by MFR **(10/21)** first leg of data processing is understood
- Reproducible

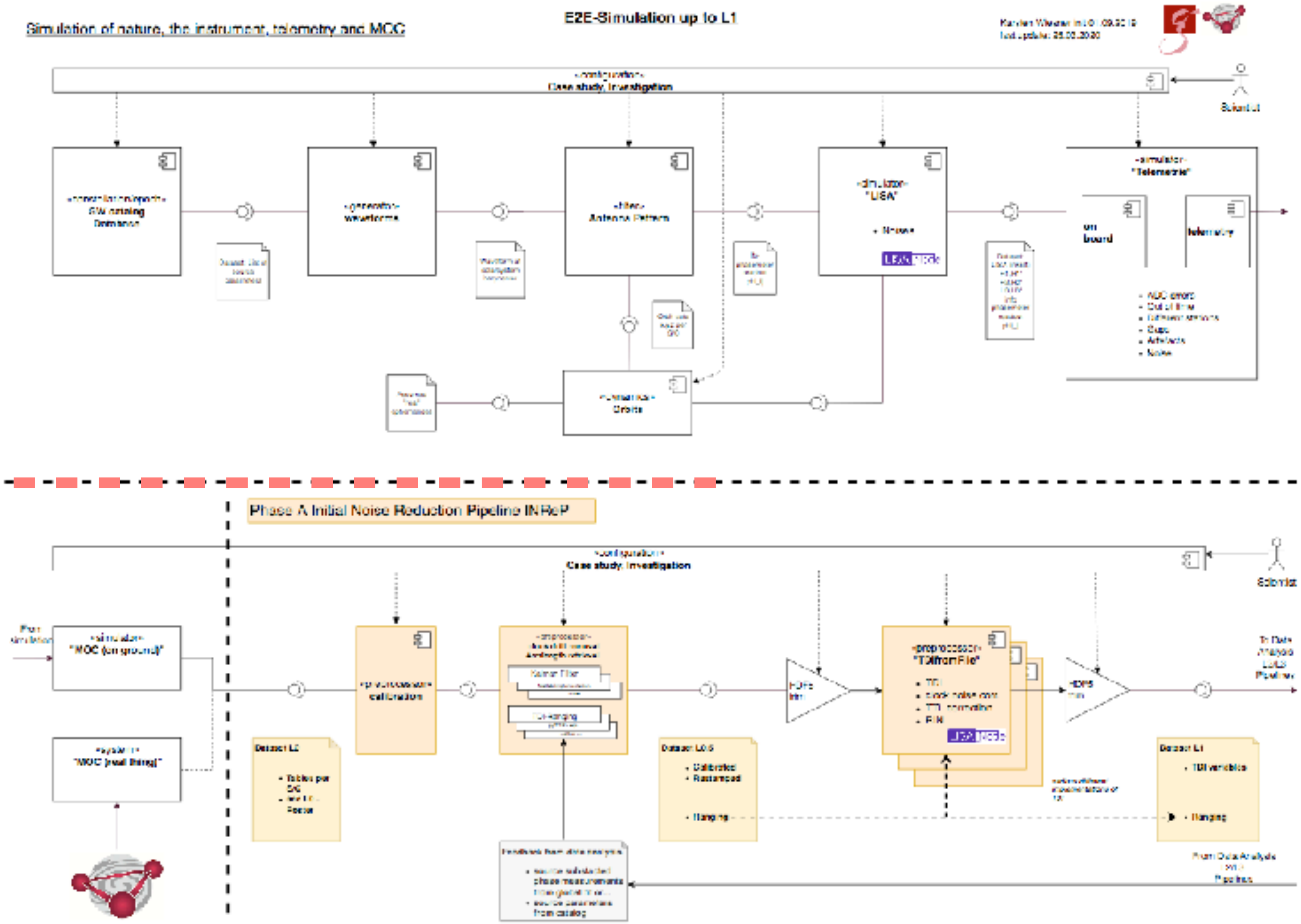


Figure LDPG WG6 INReP