LISA Technology: A Status Report

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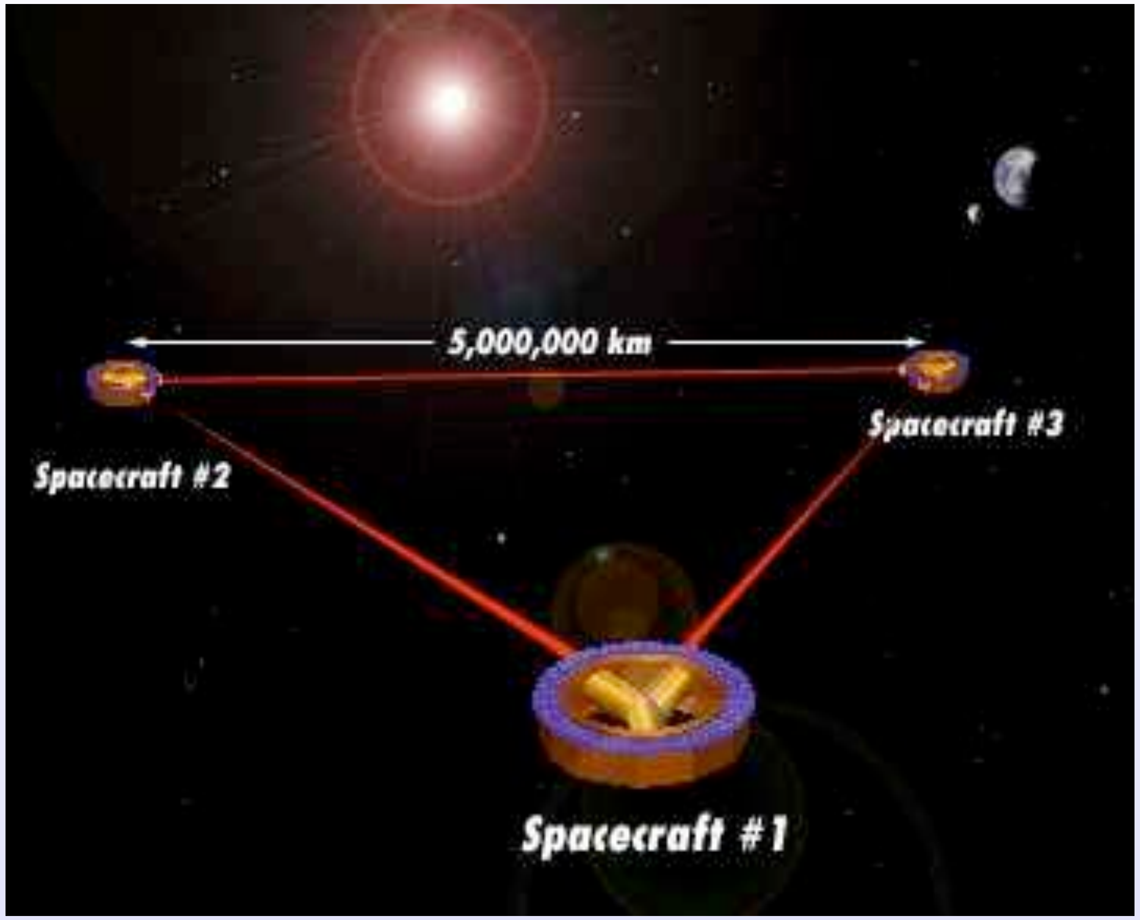
Minnesota 2010

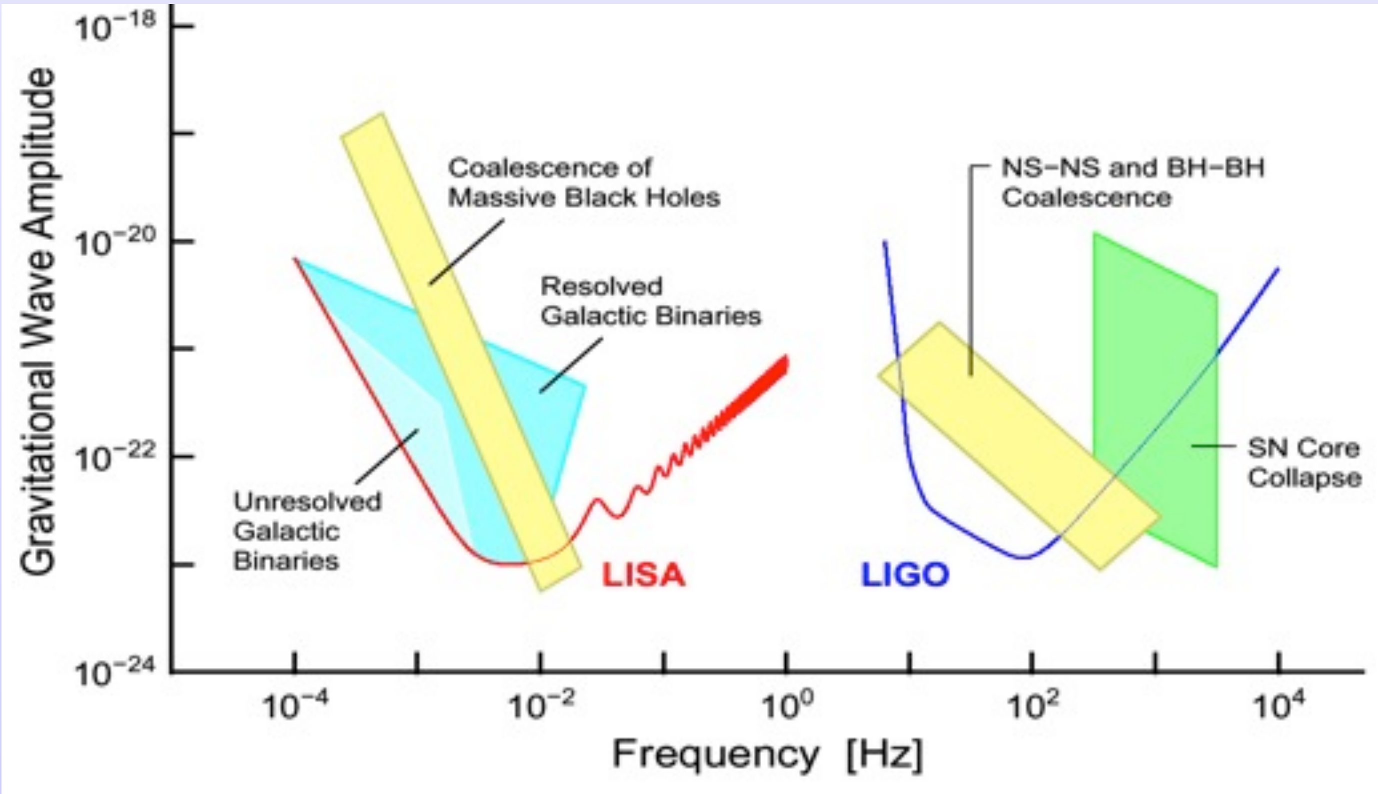
Content

- LISA Concept
  - Gravitational Reference Sensor
  - Interferometry Measurement System
- Status/Outlook

LISA Concept

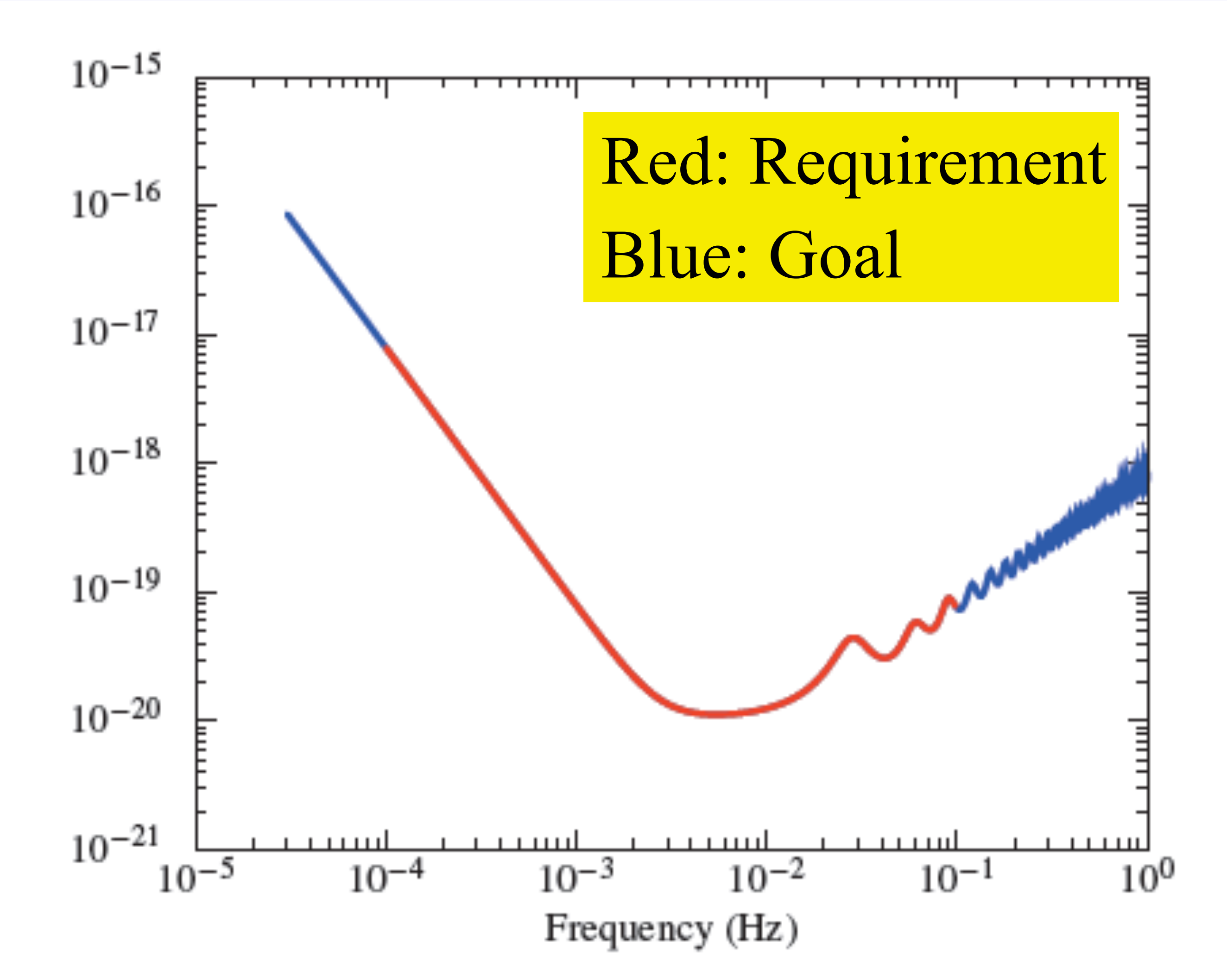


- 3 spacecraft constellation
- S/C separated by $5x10^6$km
- Two Drag-free proof masses inside each S/C
- Interferometer measure variations in proof mass distances
- Earth-trailing solar orbit



LISA Requirements

$$\text{GW-Strain: } h = \frac{\delta L}{L}$$



Limited by noise in the IMS (Interferometry Measurement System):

$$S_{\delta L}^{1/2}(f) \leq 18 \frac{\text{pm}}{\sqrt{\text{Hz}}} \times \sqrt{1 + \left(\frac{2\text{mHz}}{f}\right)^2}$$

Limited by noise (residual acceleration) in the DRS (Disturbance Reduction System):

$$S_{\delta\alpha}^{1/2}(f) \leq 3 \times 10^{-15} \frac{\text{m}}{\text{s}^2\sqrt{\text{Hz}}} \times \sqrt{1 + \left(\frac{0.1 \text{ mHz}}{f}\right)}$$

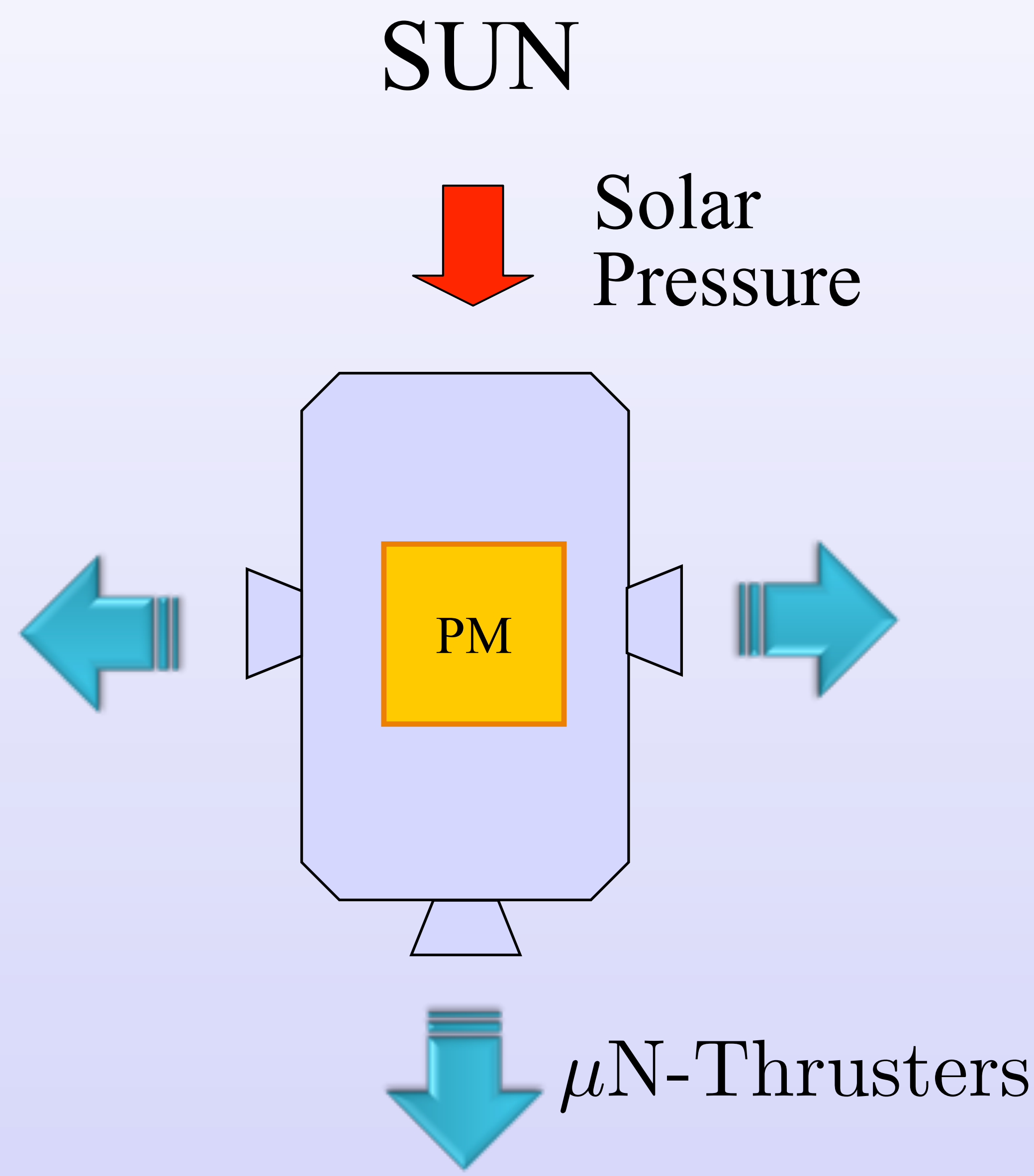
Disturbance Reduction System

Shield the Proof masses from all external forces

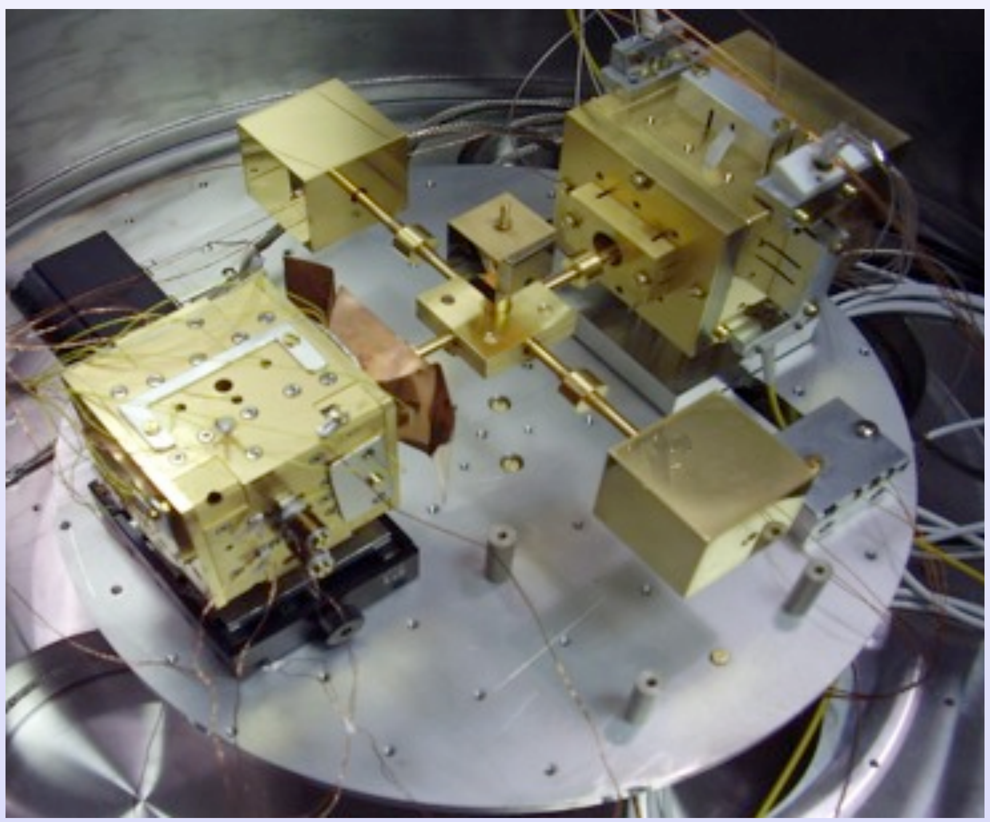
- ➔ Build a S/C around it

Drag free navigation

- ➔ Monitor S/C to PM position
- ➔ Steer the S/C around the PM



Experimental Verification of DRS



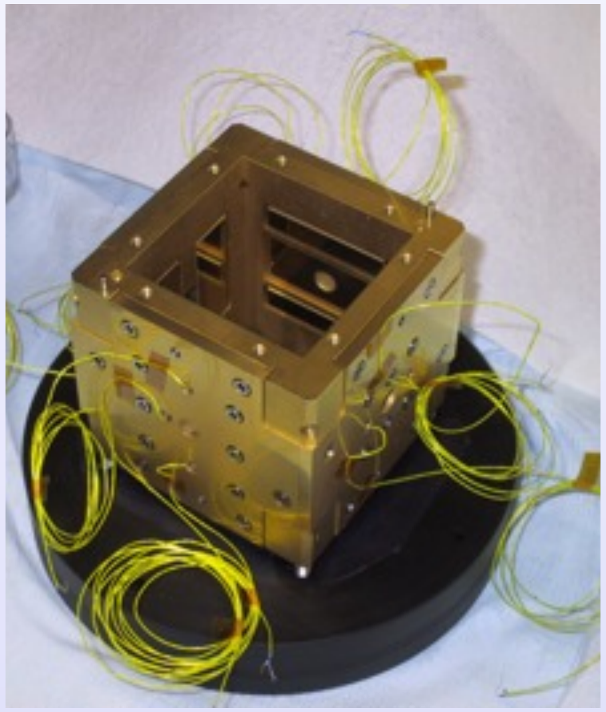
Torsion pendulum
in Trento

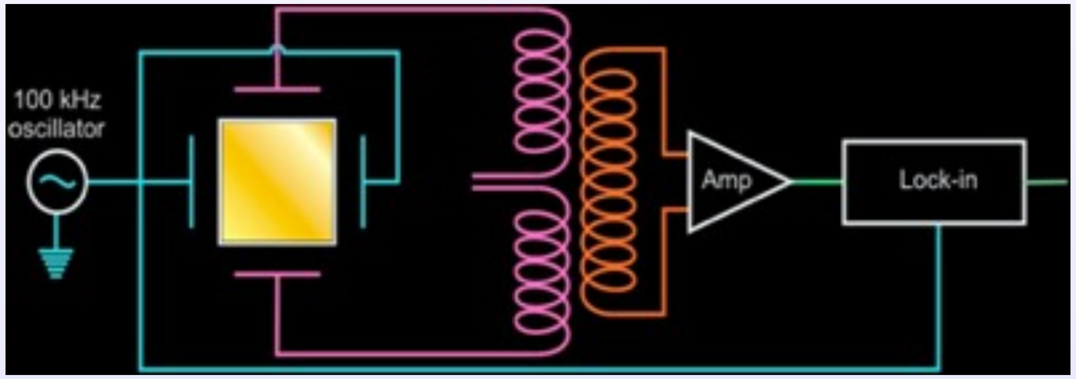
Space-based test
with LISA Pathfinder

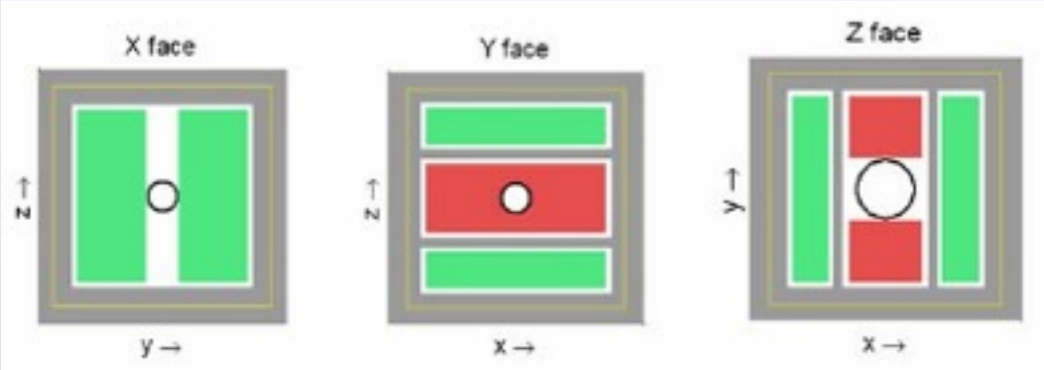
Other experiments with Gravitional Reference Sensors:

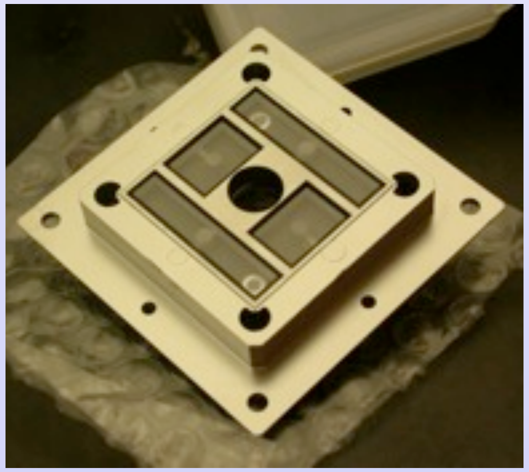
- Space: Grace, Goce, Microscope, ...
- Torsion Pendula: Adelberger, Gundlach, ...

Experimental Verification of DRS









| 6cm |

Capacitive Sensing:

$$\delta x(f) = 2\frac{\mathrm{nm}}{\sqrt{\mathrm{Hz}}}$$

$$\delta\theta(f) = 200\frac{\mathrm{nrad}}{\sqrt{\mathrm{Hz}}}$$

Spring-like Actuation:

$$k = \frac{C_X}{d^2}V_{inj}^2$$

The Noise model:

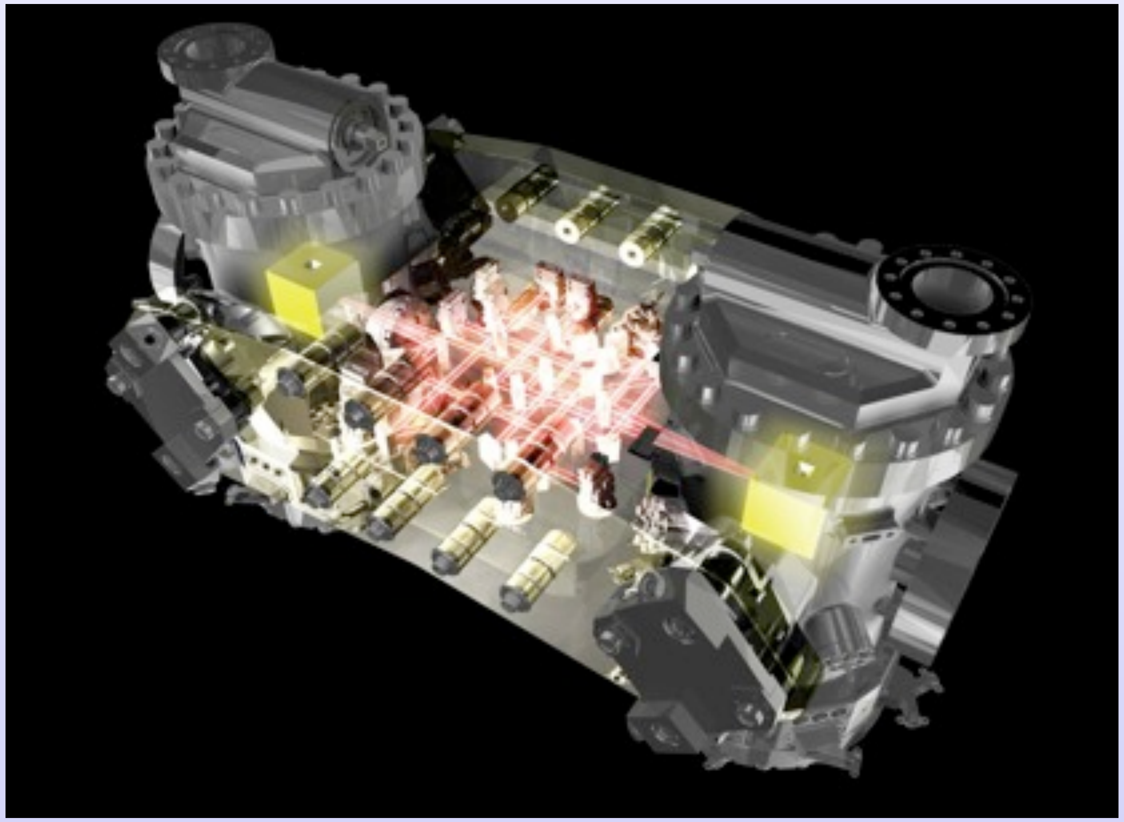
$$a_n = \frac{f_{str}}{m} + \frac{k}{m}\left(x_n + \frac{f_{S/C}}{M\omega^2}\right)$$

Experimental Verification of DRS

The Noise model:

$$a_n = \frac{f_{str}}{m} + \frac{k}{m}\left(x_n + \frac{f_{S/C}}{M\omega^2}\right)$$

- **Stray Forces:**
  - **Gravitation**
  - **Electro-magnetic**
  - **Radiation pressure**
  - **Residual gas**
  - **...**



Status of LTP

- All flight hardware has been delivered except
  - FEEPs $(\mu$N-thrusters$)$
  - Final Caging Mechanism
- Engineering model of Caging mechanism has been tested
- All subsystems are now being integrated into engineering model
- Flight unit is under construction
- S/C+Payload is just passed 'Transfer orbit thermal balance' tests (see pic)
- Next tests: Environmental and vibrational tests mid 2011

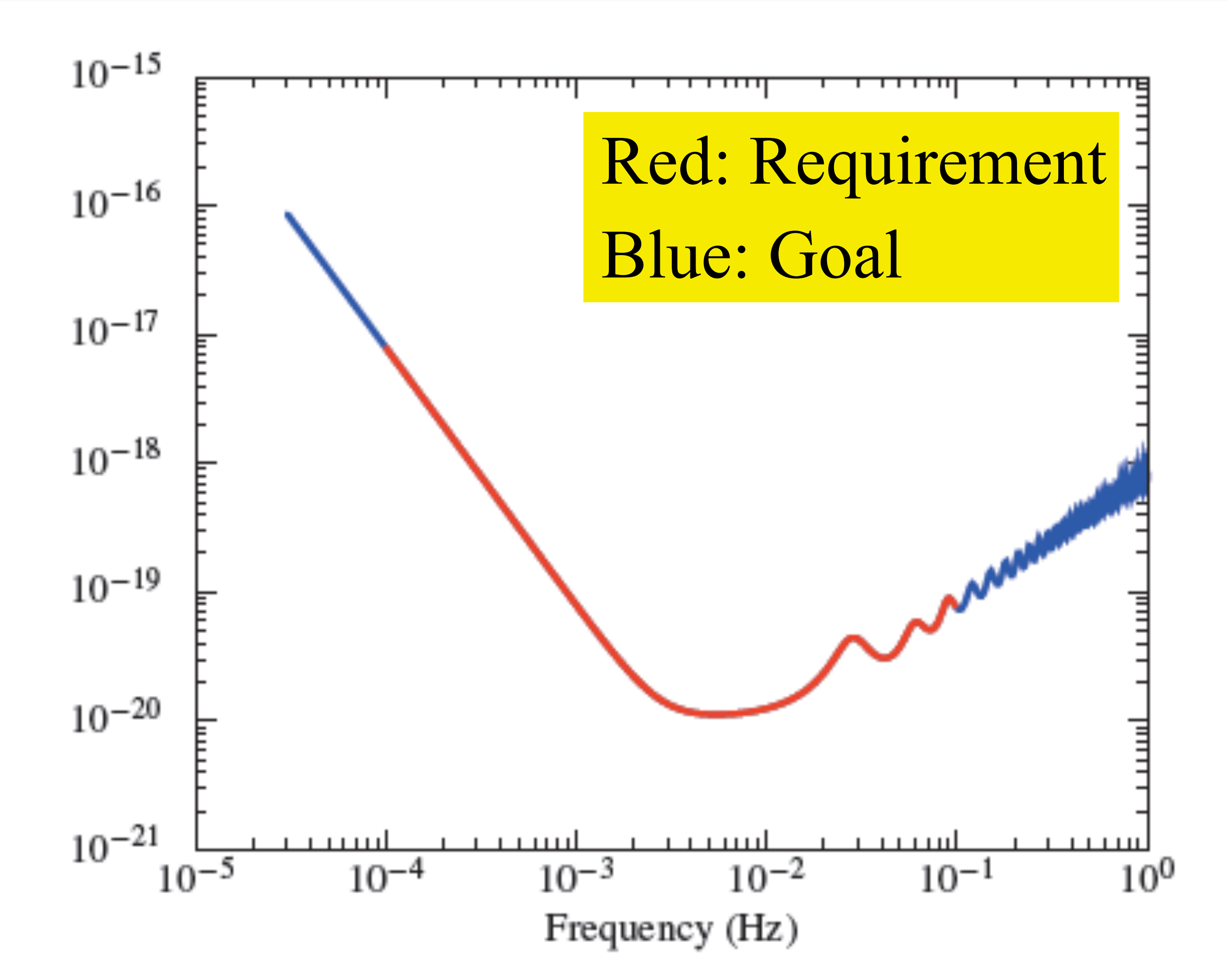
To be launched 2012/13

LISA Requirements

GW-Strain: $h = \frac{\delta L}{L}$

Limited by noise in the IMS (Interferometry Measurement System):

$$S_{\delta L}^{1/2}(f) \leq 18 \frac{\text{pm}}{\sqrt{\text{Hz}}} \times \sqrt{1 + \left(\frac{2\text{mHz}}{f}\right)^2}$$



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IMS

IMS Environment:

Orbits cause

- relative Motion of Proof Masses:

$$v = \pm 10 \frac{m}{s}$$

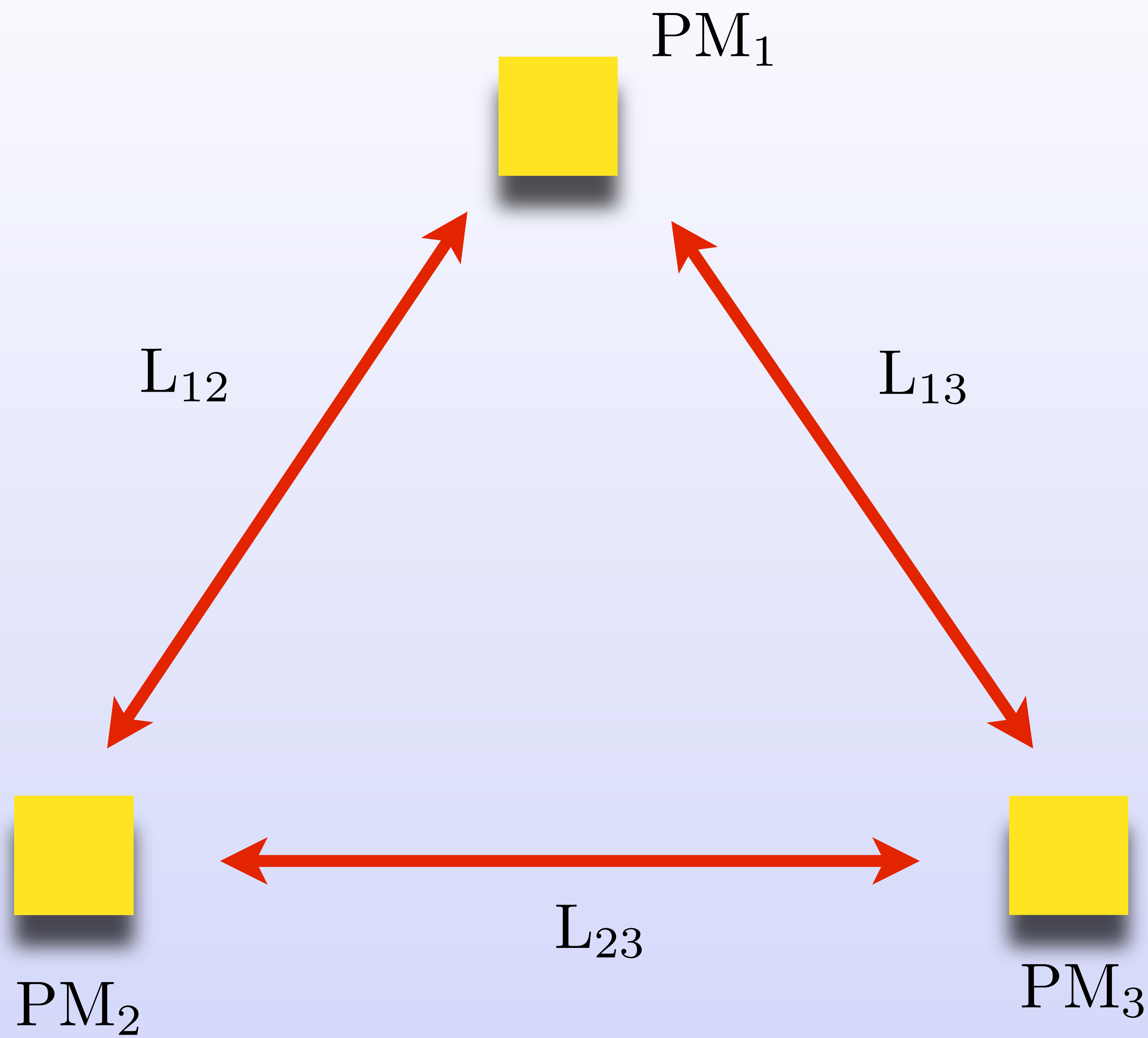
Changing

- Doppler shifts
- Point ahead angle

- Changes angles:

$$\Delta\phi \approx \pm 0.5^\circ$$

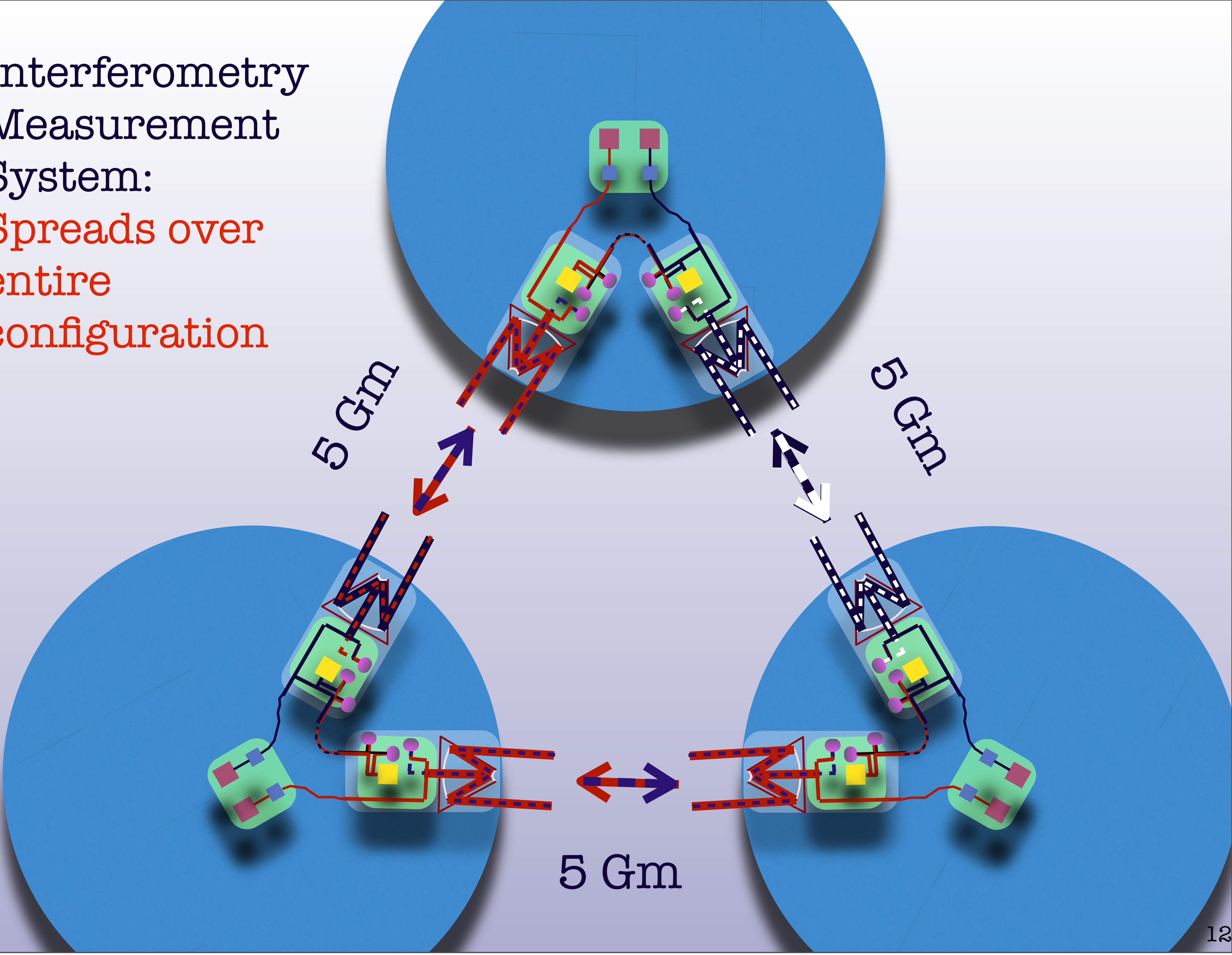
- Maintain Alignment

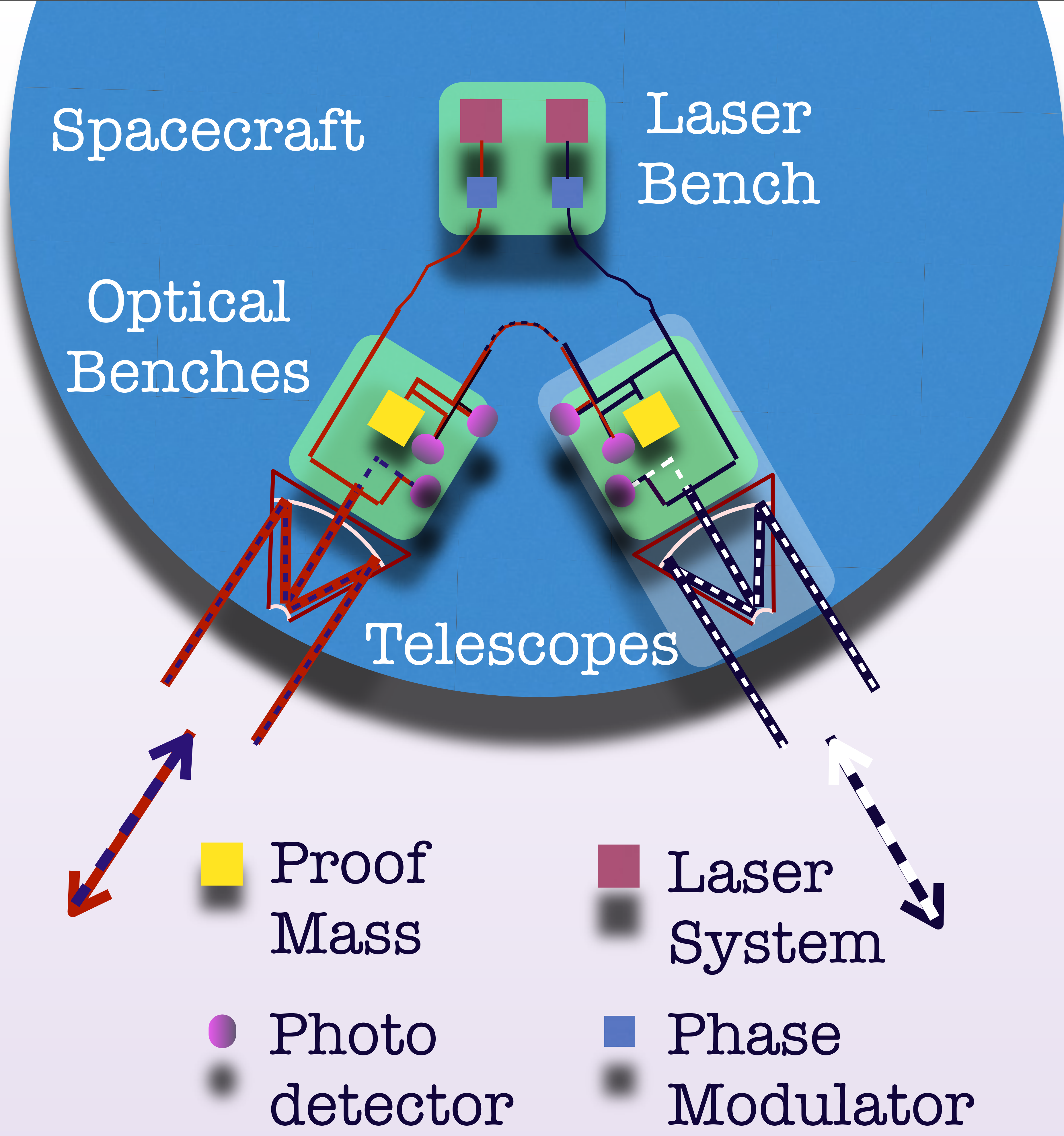


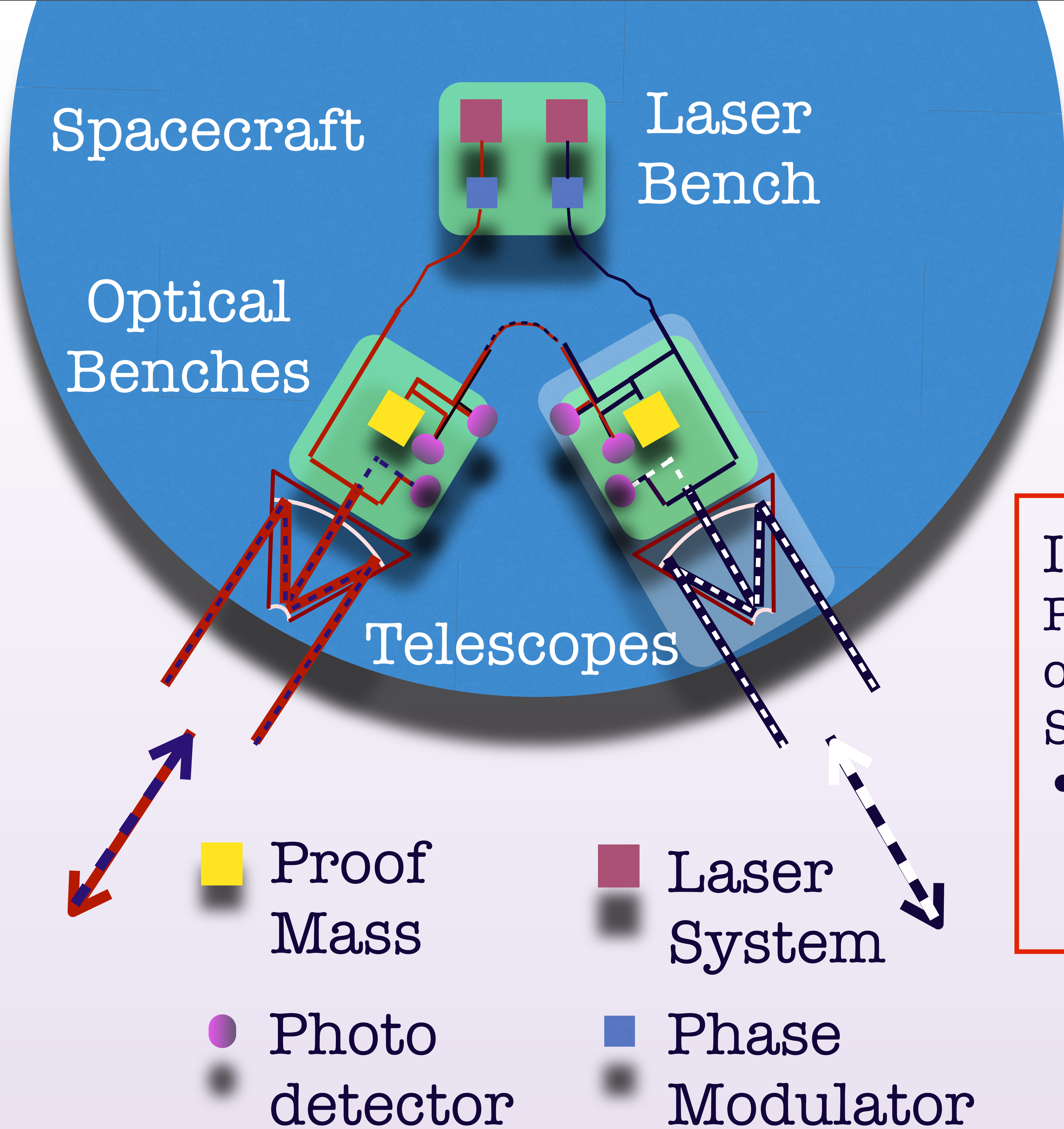
Very dynamic Interferometer

Interferometry Measurement System:

Spreads over entire configuration



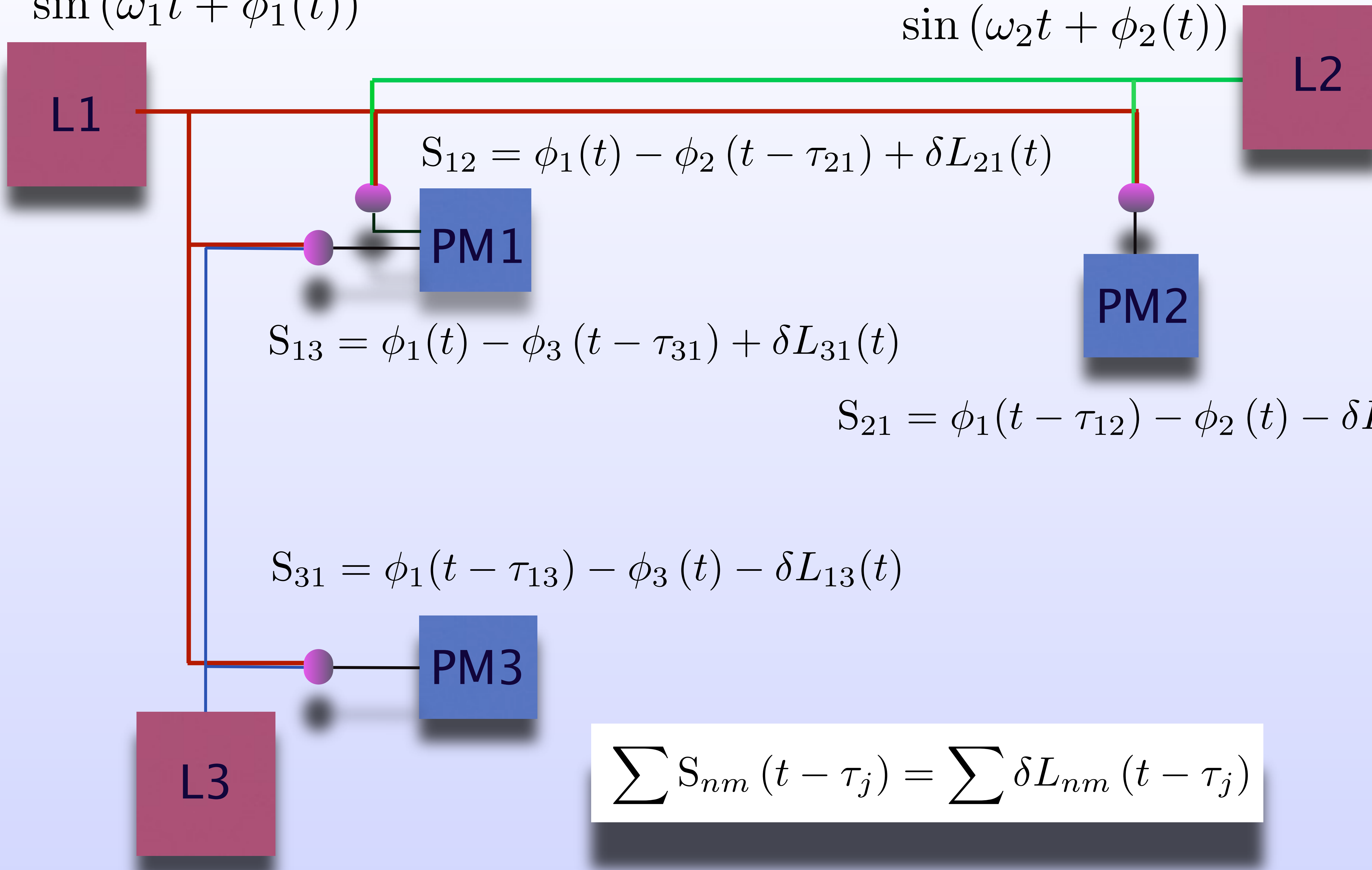

Spacecraft
Laser Bench
Optical Benches
Telescopes
Proof Mass
Laser System
Photo detector
Phase Modulator



IMS-Signals:
Phase Evolution of Laser Beat Signals

- Dominated by laser frequency noise

Time Delay Interferometry



$$\sin\left(\omega_1 t + \phi_1(t)\right)$$

$$\sin\left(\omega_2 t + \phi_2(t)\right)$$

$$\mathrm{S}_{12} = \phi_1(t) - \phi_2\left(t - \tau_{21}\right) + \delta L_{21}(t)$$

$$\mathrm{S}_{13} = \phi_1(t) - \phi_3\left(t - \tau_{31}\right) + \delta L_{31}(t)$$

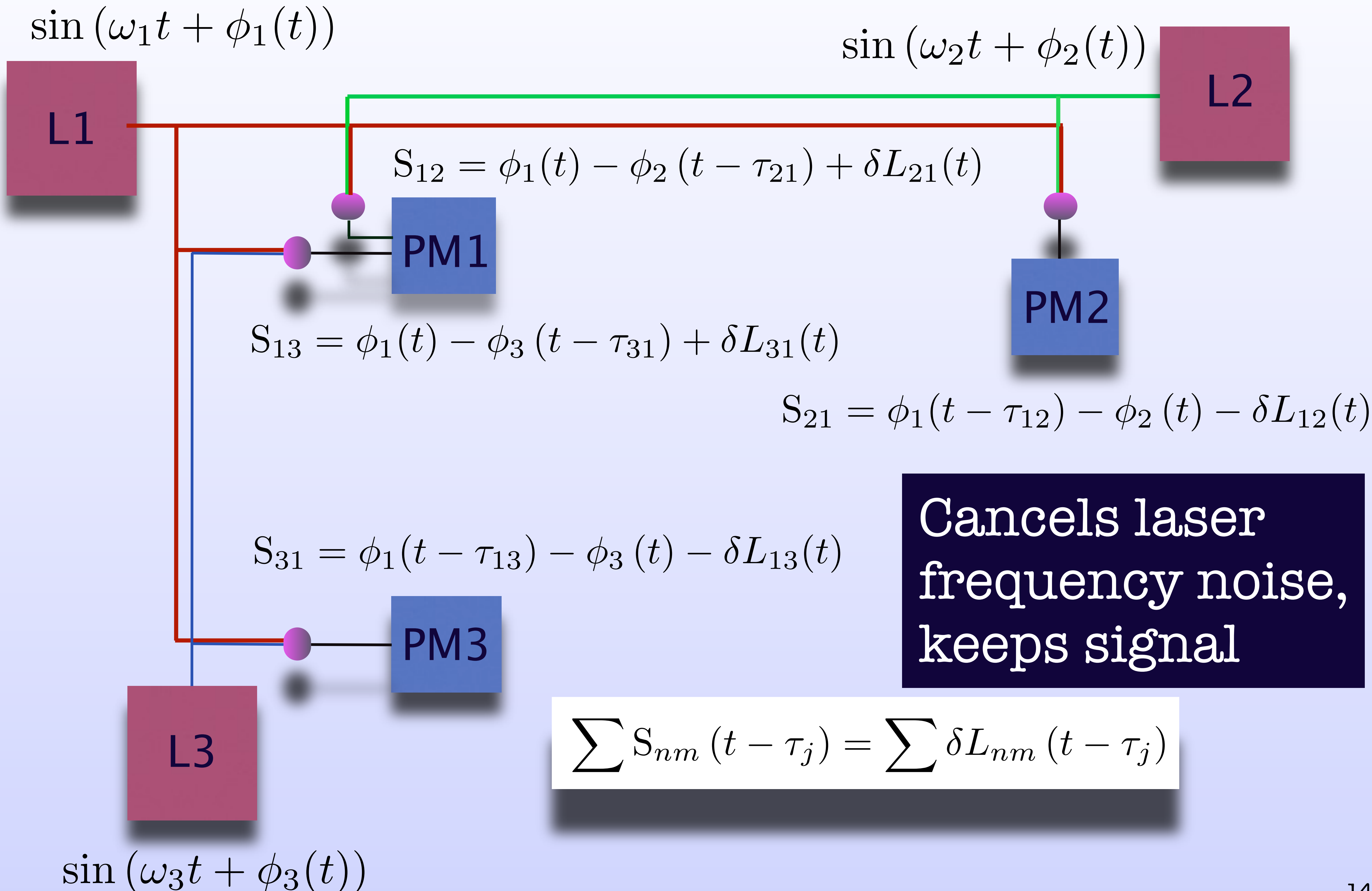
$$\mathrm{S}_{21} = \phi_1(t - \tau_{12}) - \phi_2\left(t\right) - \delta L_{12}(t)$$

$$\mathrm{S}_{31} = \phi_1(t - \tau_{13}) - \phi_3\left(t\right) - \delta L_{13}(t)$$

$$\sum \mathrm{S}_{nm}\left(t - \tau_j\right) = \sum \delta L_{nm}\left(t - \tau_j\right)$$

$$\sin\left(\omega_3 t + \phi_3(t)\right)$$

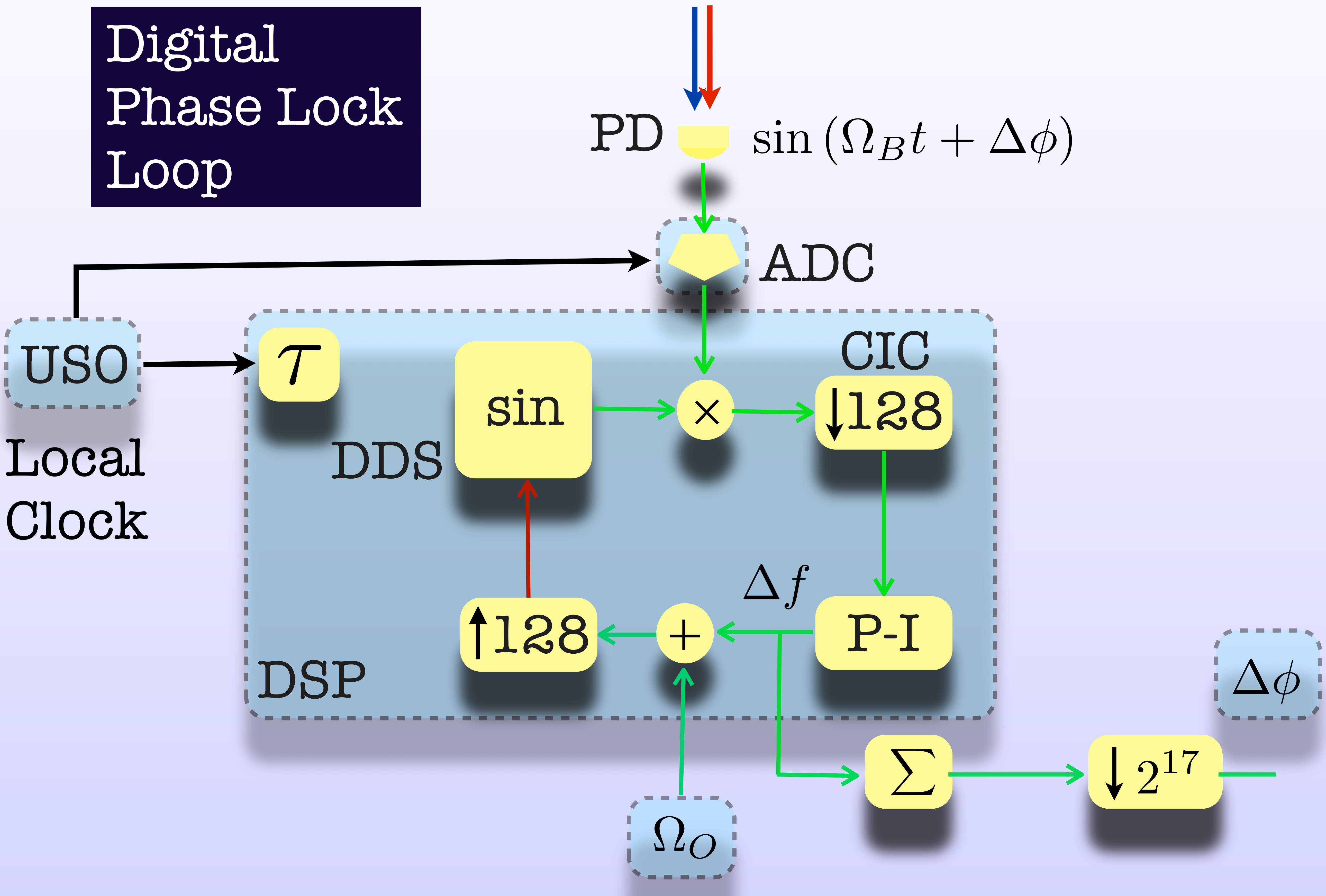
Time Delay Interferometry



Cancels laser frequency noise, keeps signal

$$\sum S_{nm}(t - \tau_j) = \sum \delta L_{nm}(t - \tau_j)$$

The Tool: Phasemeter



Phasemeter

Requirements:

- Phase Noise $$\delta\phi(f) < \frac{2\pi}{\lambda}\frac{1\mathrm{pm}}{\sqrt{\mathrm{Hz}}} \approx 2\pi \cdot 10^{-6}\frac{\mathrm{rad}}{\sqrt{\mathrm{Hz}}}$$

➡ Diff. Clock Noise: $$\delta t(f) < \frac{\delta\phi(f)}{\Omega_B} < 0.05\frac{\mathrm{ps}}{\sqrt{\mathrm{Hz}}}$$

Residual noise due to laser frequency noise:

$$\delta\phi = 2\pi\delta\nu\Delta\tau$$

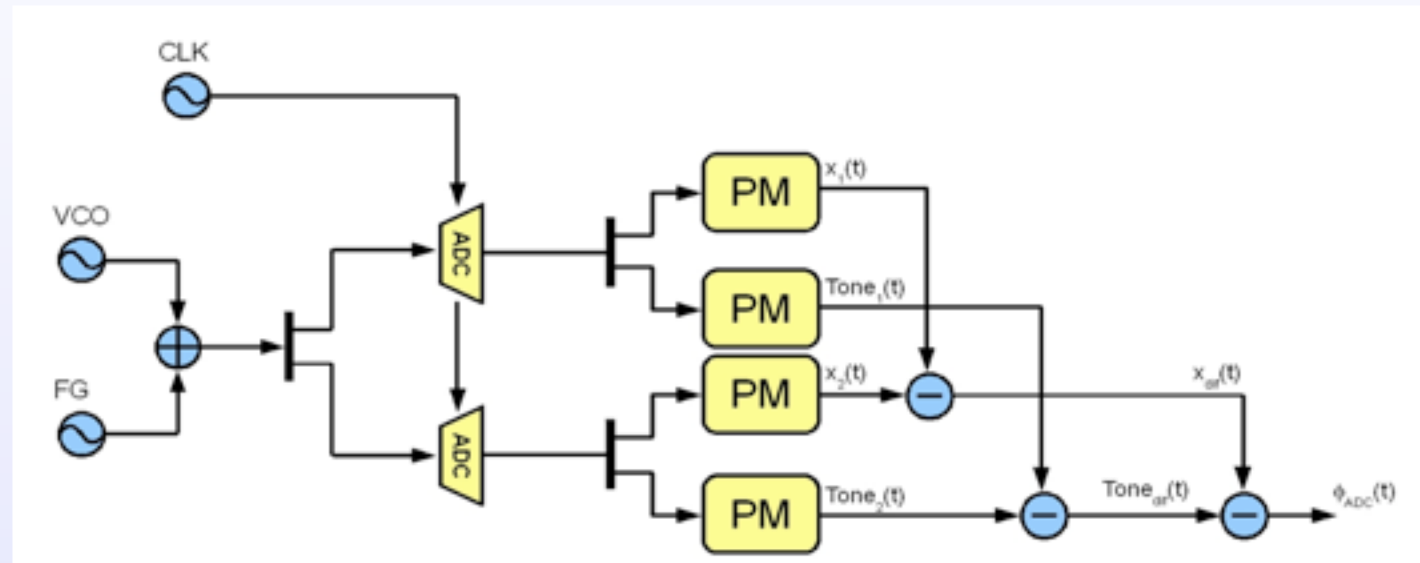
➡ Timing (Ranging): $$\Delta\tau = 3\ \mathrm{ns}\ \approx\ \Delta L = 1\ \mathrm{m}$$

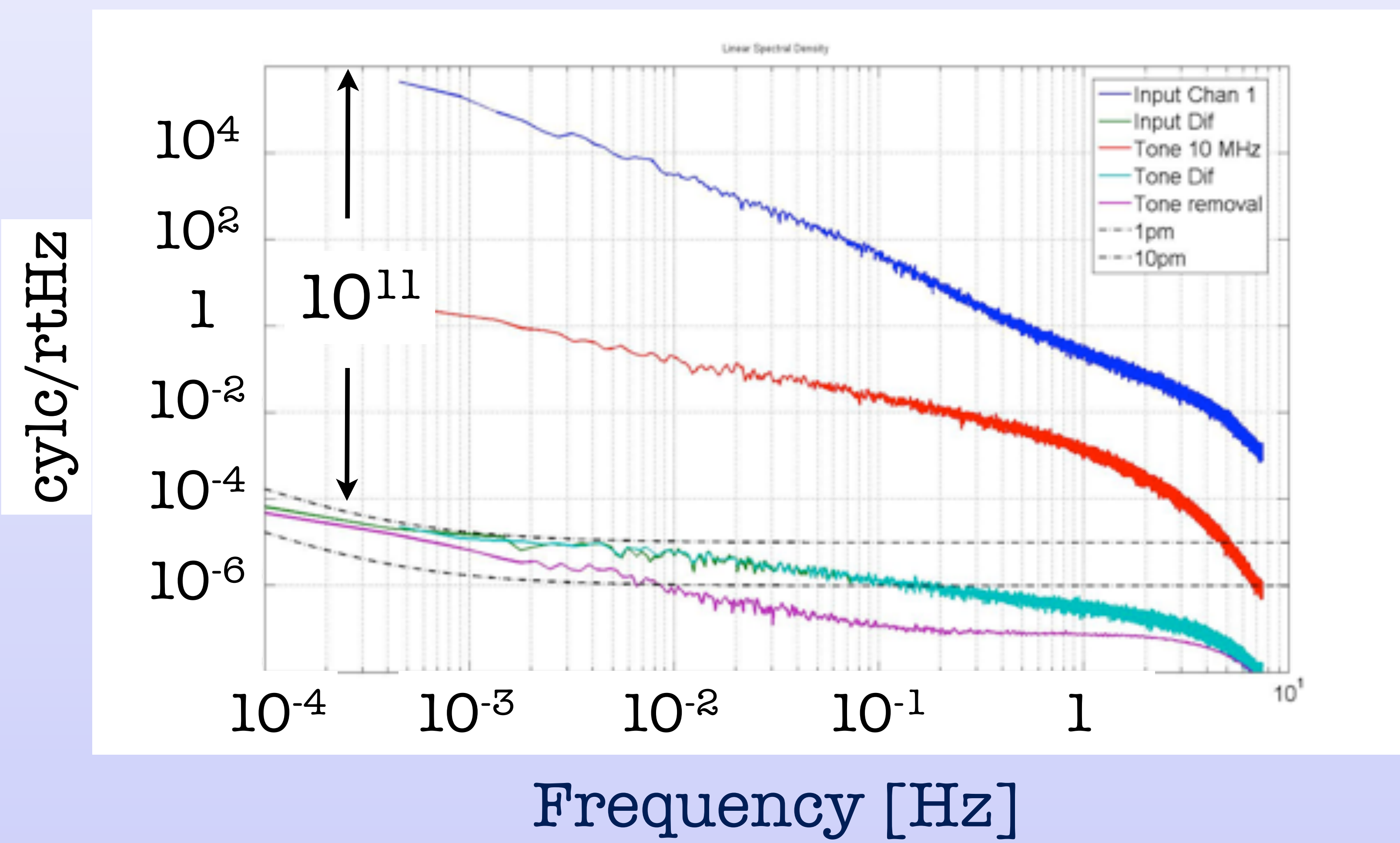
➡ Laser Frequency Noise: $$\delta\nu(f) < 141\frac{\mathrm{Hz}}{\sqrt{\mathrm{Hz}}}\sqrt{1 + \left(\frac{2.8\ \mathrm{mHz}}{f}\right)^4}$$

Phasemeter Status

- Digital Part:
  - Filters
  - Digital Noise

Meet requirements



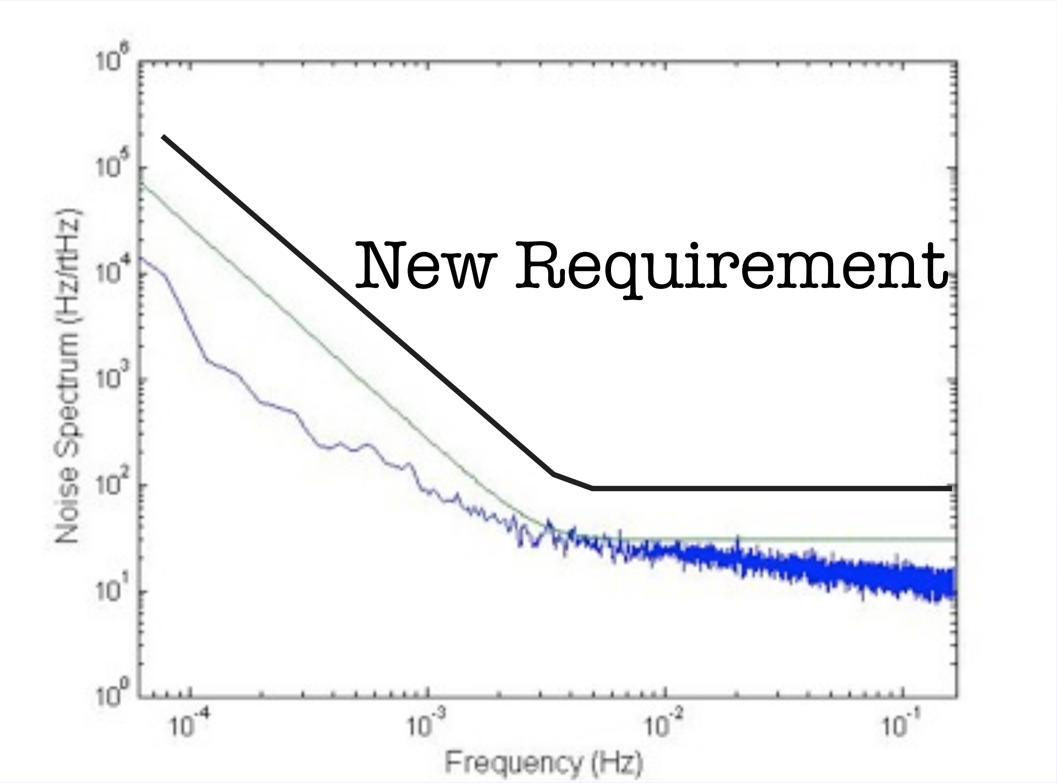


- ADCs:
  - Timing Jitter
  - Dispersion

Might need
- Pilot tone
- Temperature stabilization

Laser Frequency Noise

$$\delta\nu(f) < 141 \frac{\mathrm{Hz}}{\sqrt{\mathrm{Hz}}} \sqrt{1 + \left(\frac{2.8\ \mathrm{mHz}}{f}\right)^4}$$



Stabilized to Zerodur Reference Cavity using PDH

Options:

- Heterodyne Interferometry use LISA Phasemeter
  - ➡ Cavity
  - ➡ Mach-Zehnder (LTP-style)
- Arm Locking

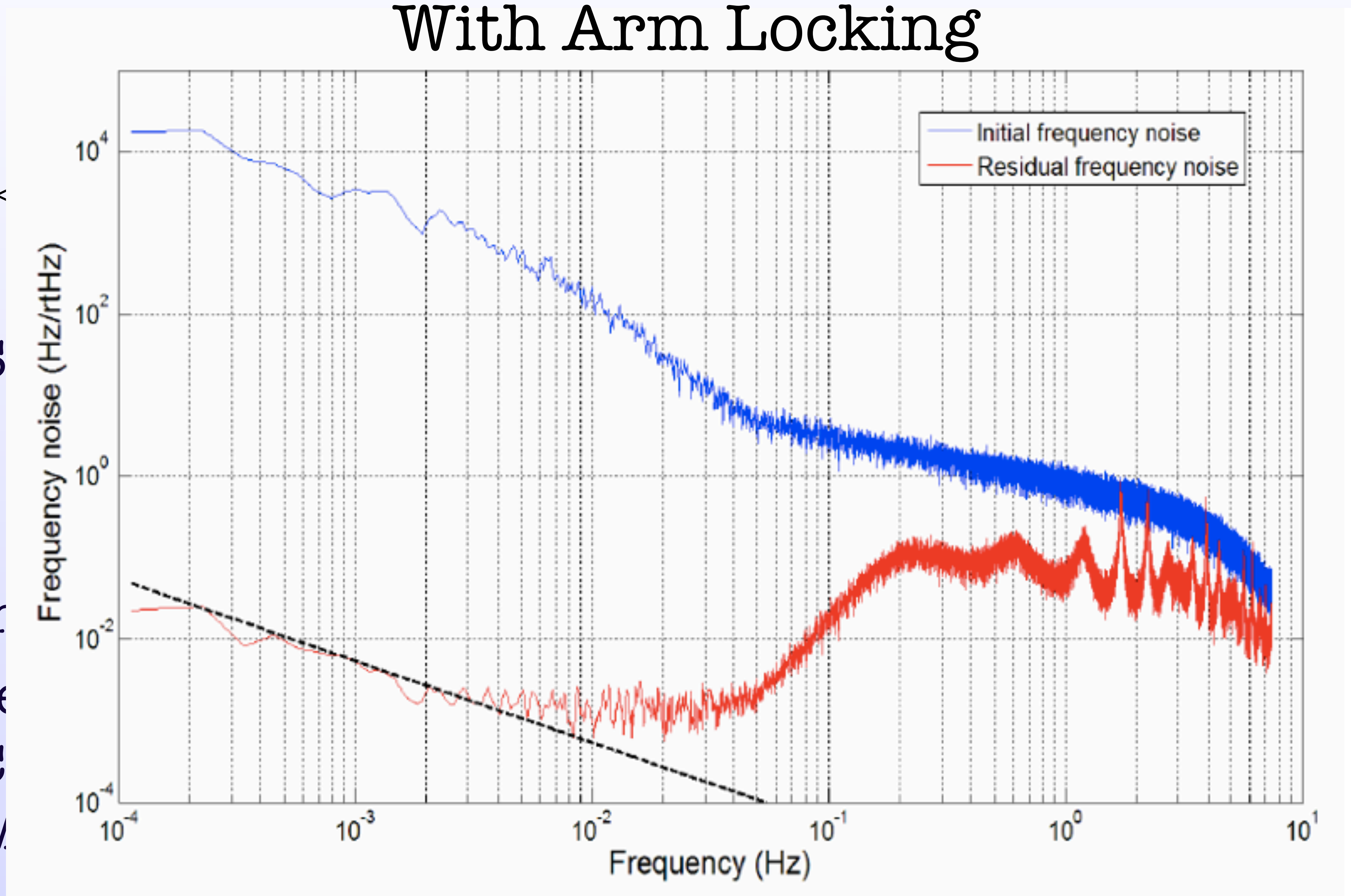
Laser Frequency Noise

$\delta\nu(f)$ <

S

Optior

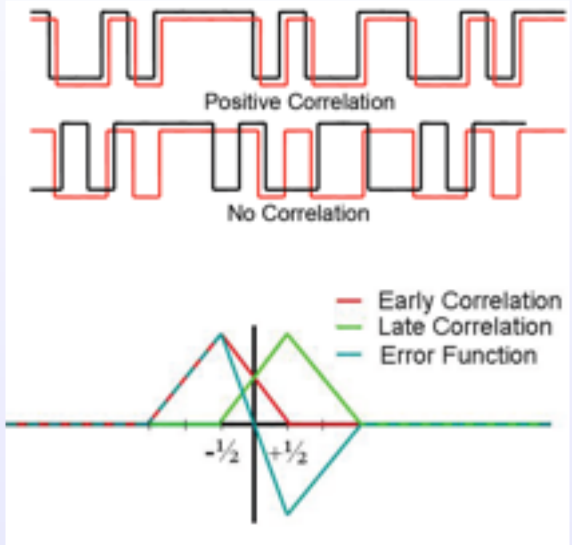
- Hete
  - ➡ C
  - ➡ M
- Arm Locking

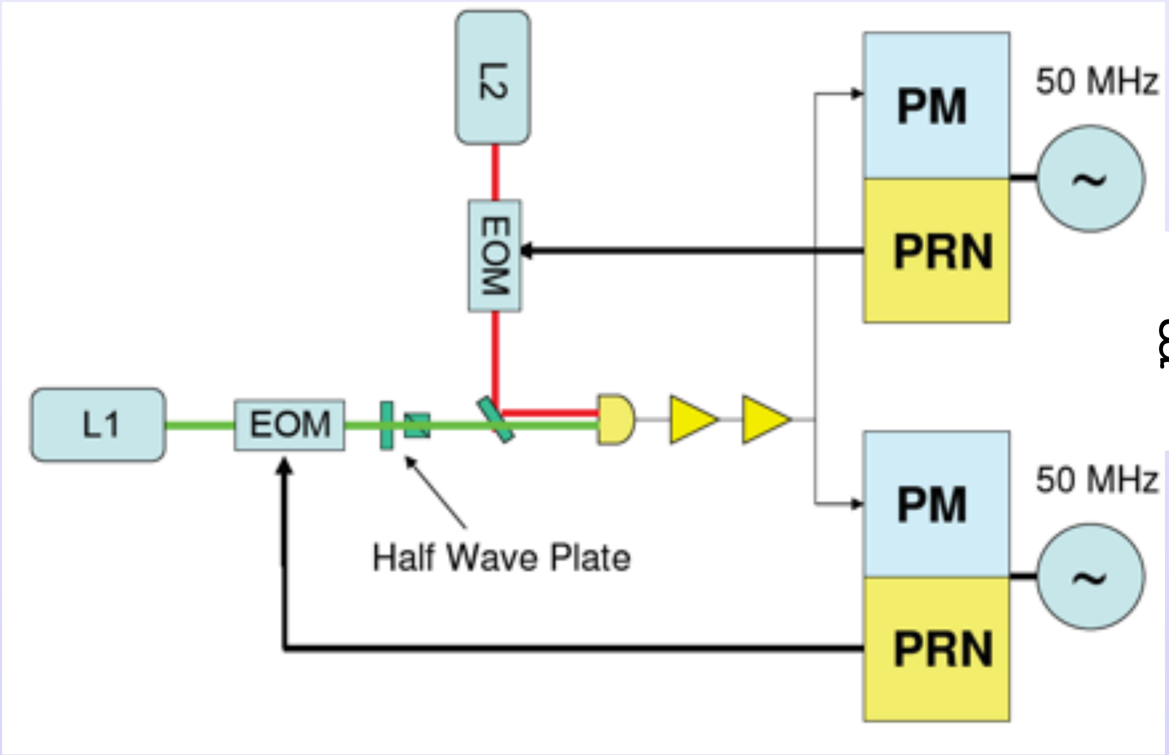


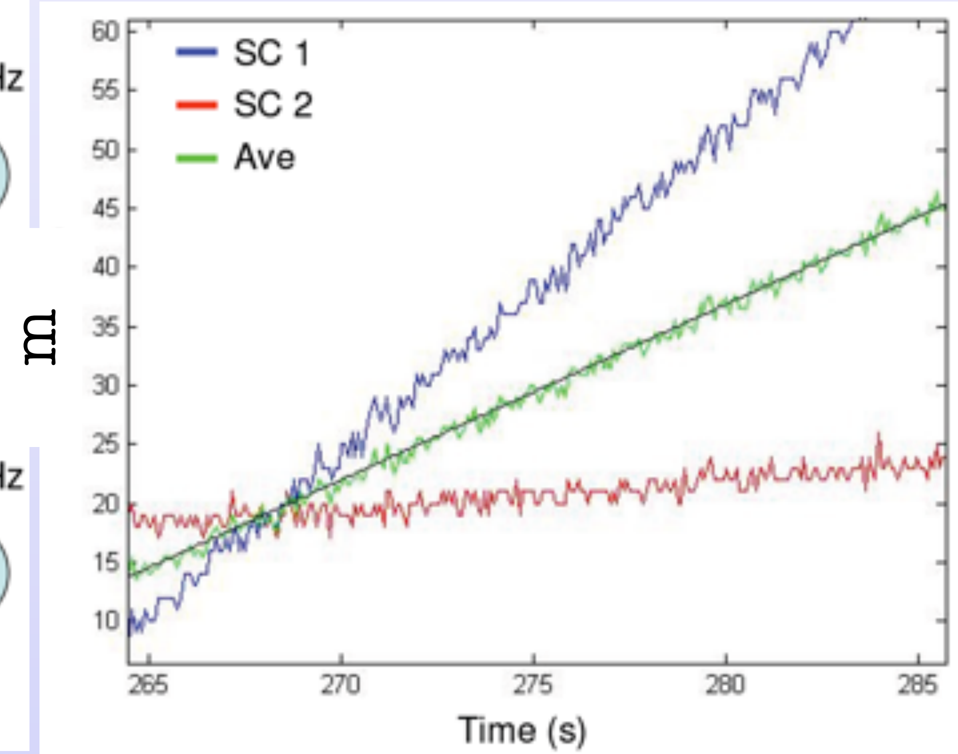
Ranging

PRN Ranging:

- Modulate/Demodulate Carrier/Carrier Beat Phase with PRN
- Known local start times used to synchronize clocks





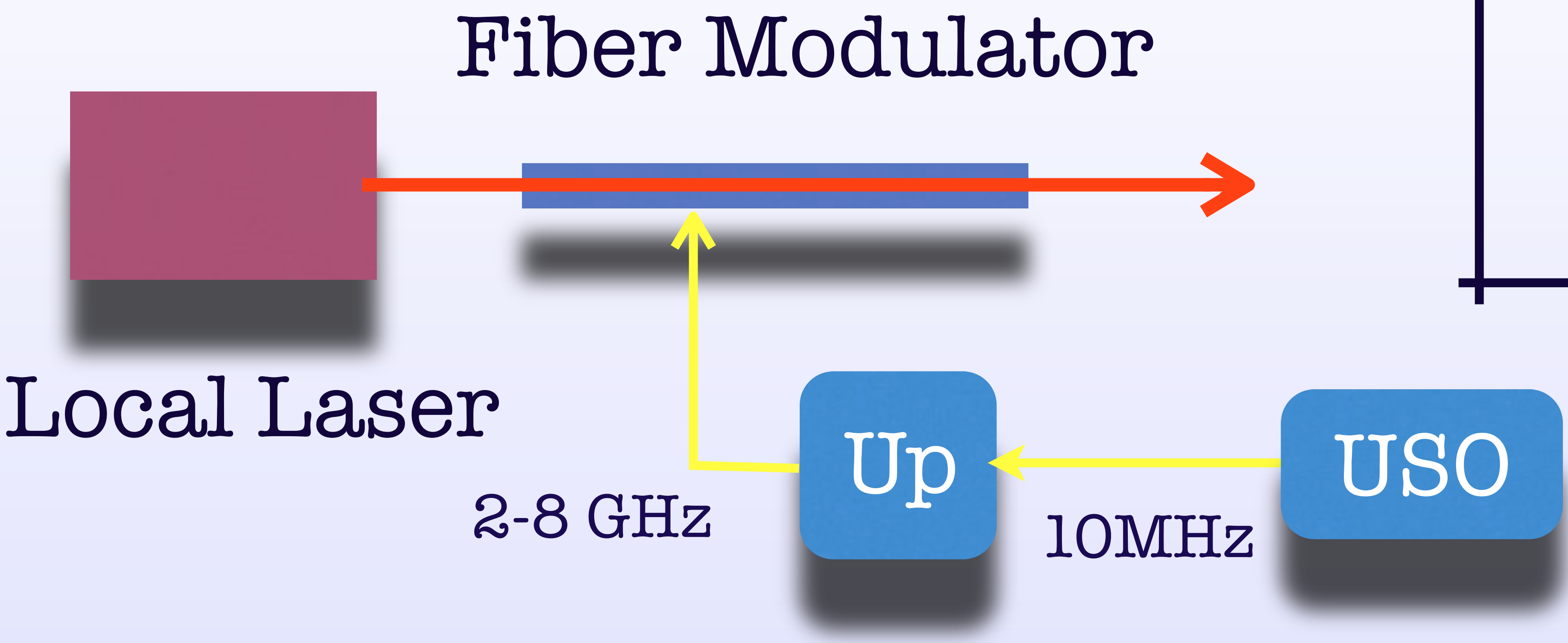


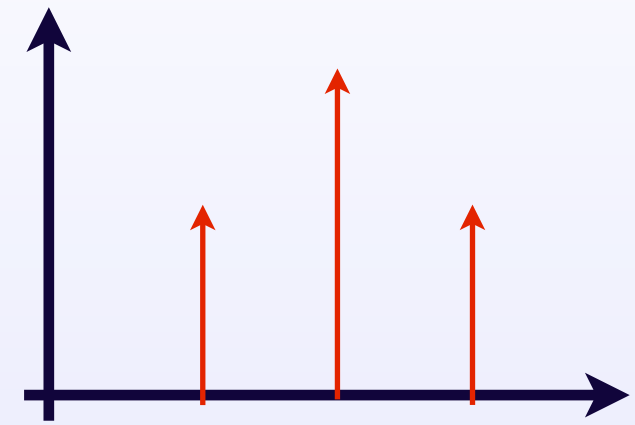
Measures also

- S/C velocities
- Differential Clock rates

Inter S/C Communication: Switch Sign of PRN Code

Clock Noise





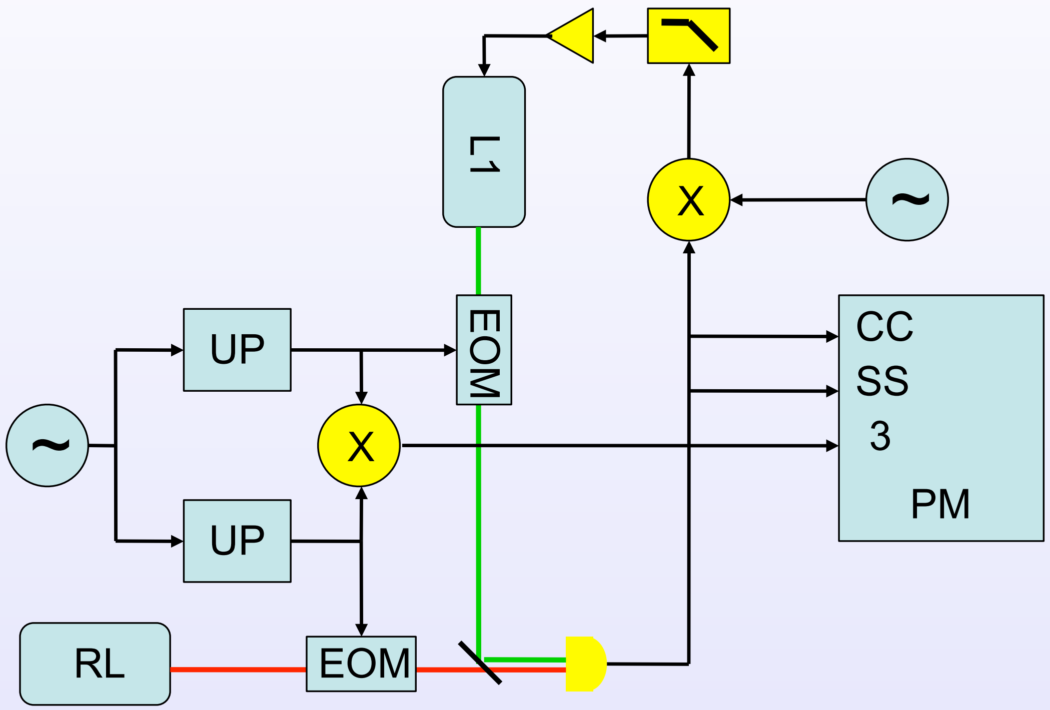
- Sidebands carry clock noise
- SB/SB beat 1MHz off from Carrier/Carrier beat
- SB/SB phase - Carrier/Carrier beat gives clock noise

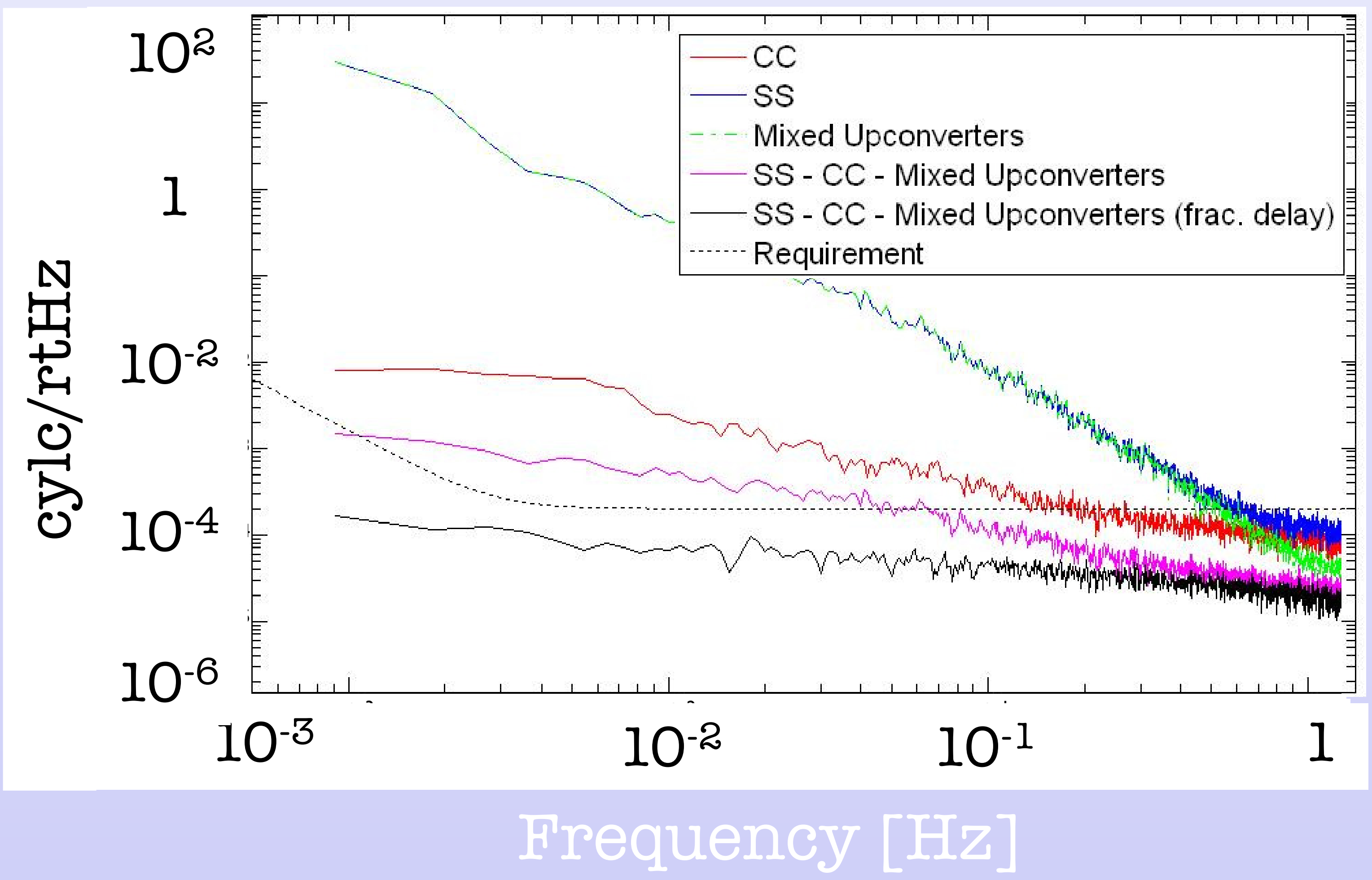
Clock Noise

Phase Fidelity of Fiber Modulator:

- Requirement relaxed by

$$\frac{20\ \mathrm{MHz}}{f_{Mod}}$$





Successfully tested at AEI, JPL, UF

- integrated at JPL and UF into testbeds

Additional signals for TDI combinations

TDI for LISA

LISA uses 18+ Signals:

to cancel:

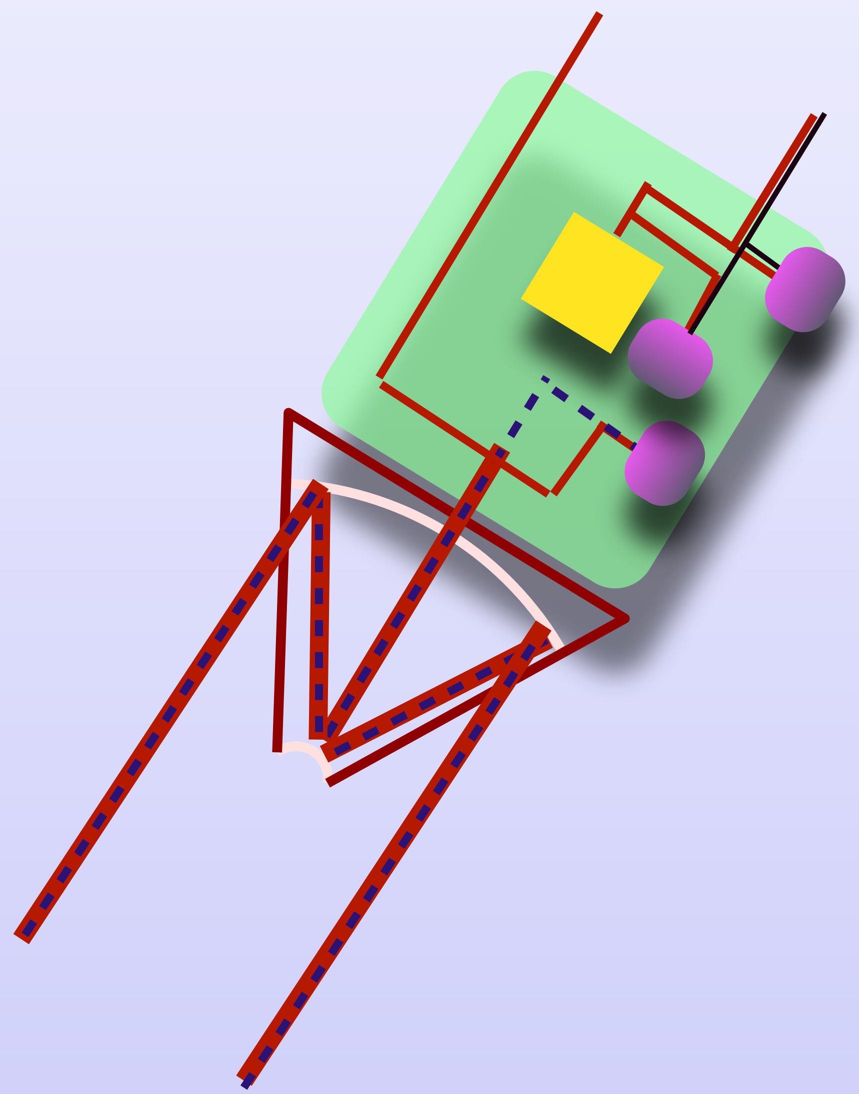
- Laser frequency noise
- Spacecraft motion

to generate:

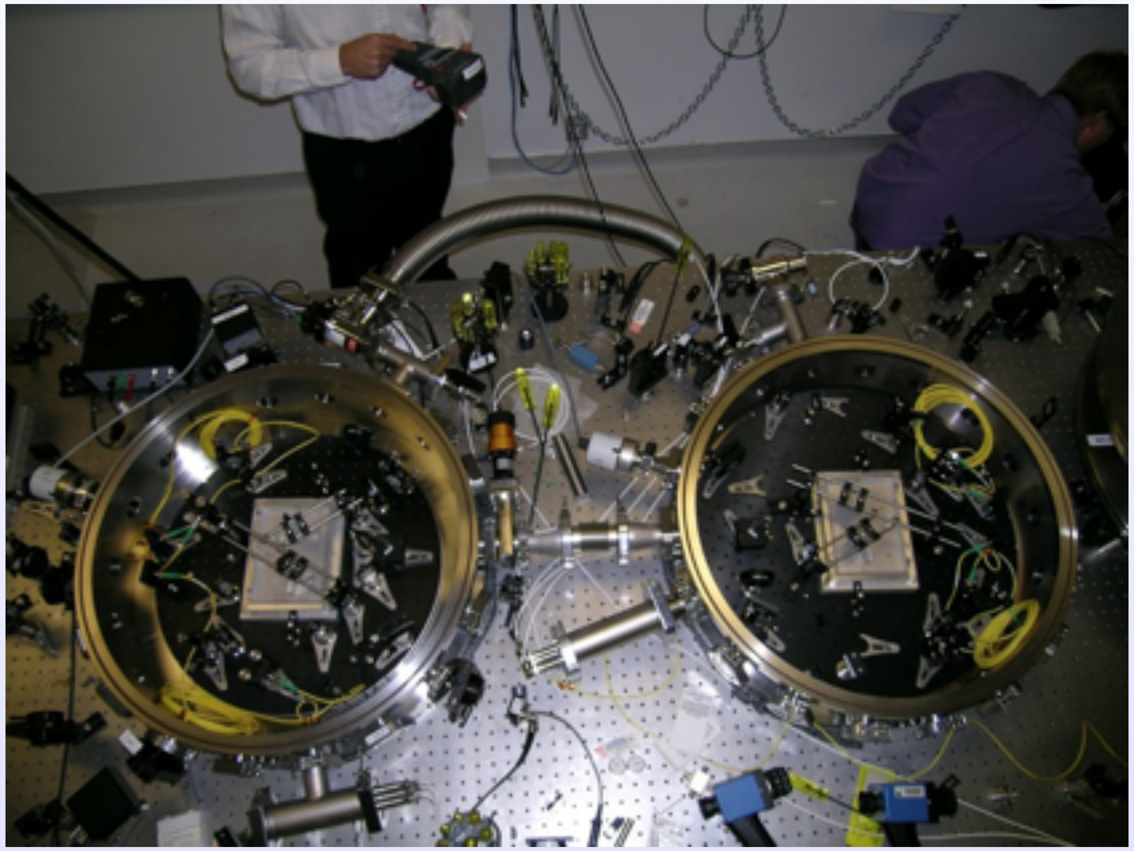
- TDI Combinations
  - Depend only on PM motion

3 Types of IFO:

1. Bench to Bench
   ➡ Measure S/C to S/C motion
2. Backlink
   ➡ Correlate the local laser
3. Proof mass to Bench
   ➡ Measure PM to S/C motion



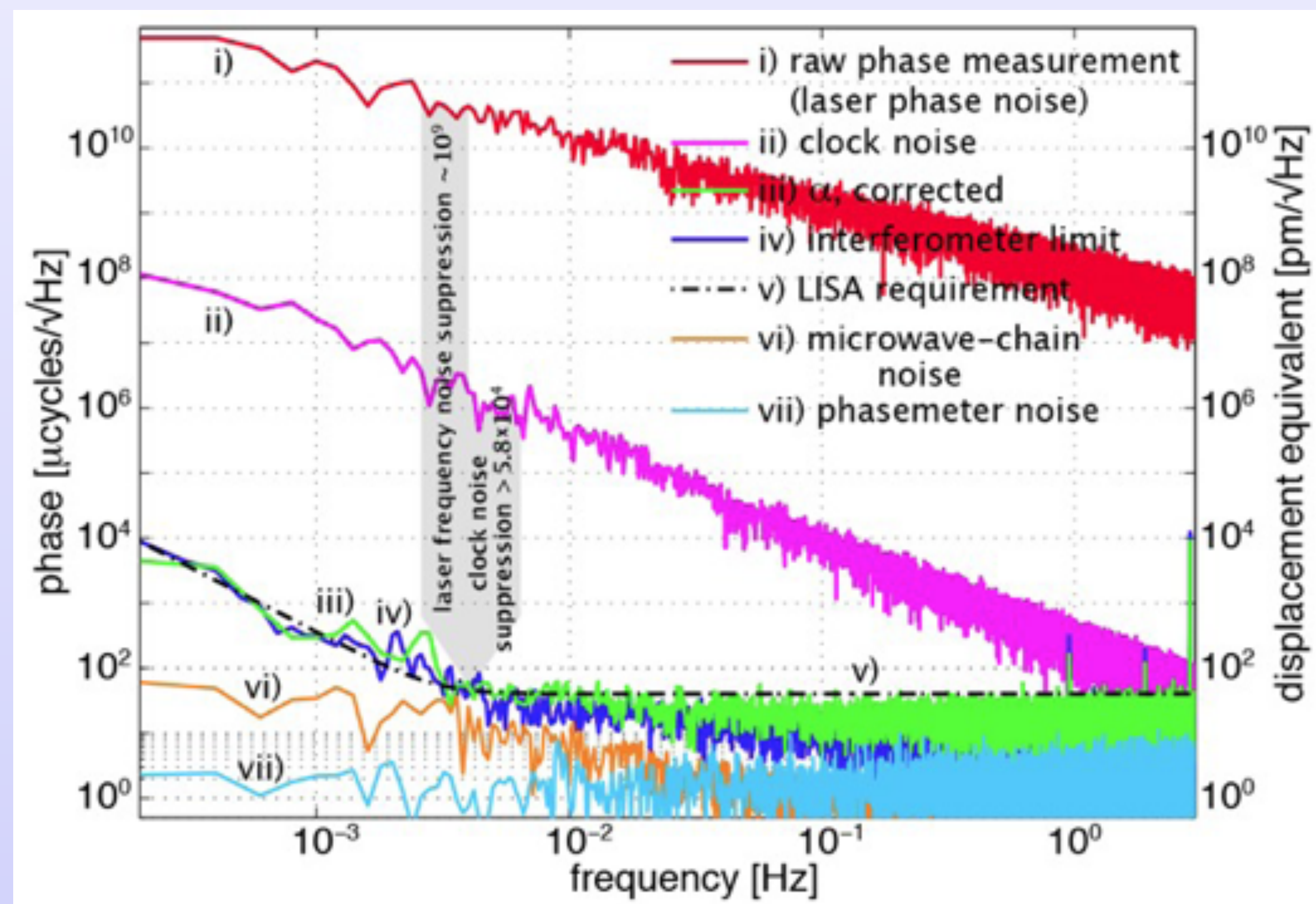
JPL Testbed



* Injected 800Hz/rtHz laser frequency noise
* 6 GHz clock noise transfer
* PRN Ranging
* Two independent multi-channel PM
* Two independent clocks (USOs)

Post-processed TDI:

* Fractional delay filtered
* Time delays determined by PRN
* Clock Noise corrected
* 10^9 suppressen at 3mHz

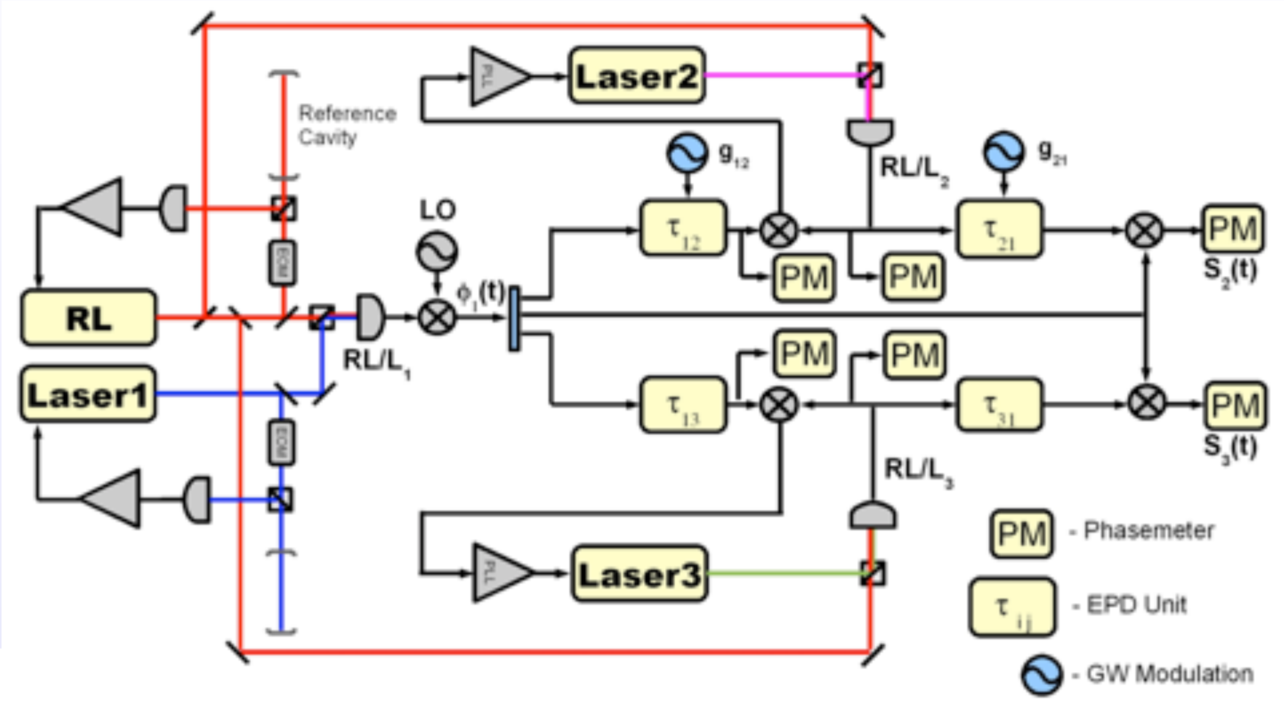


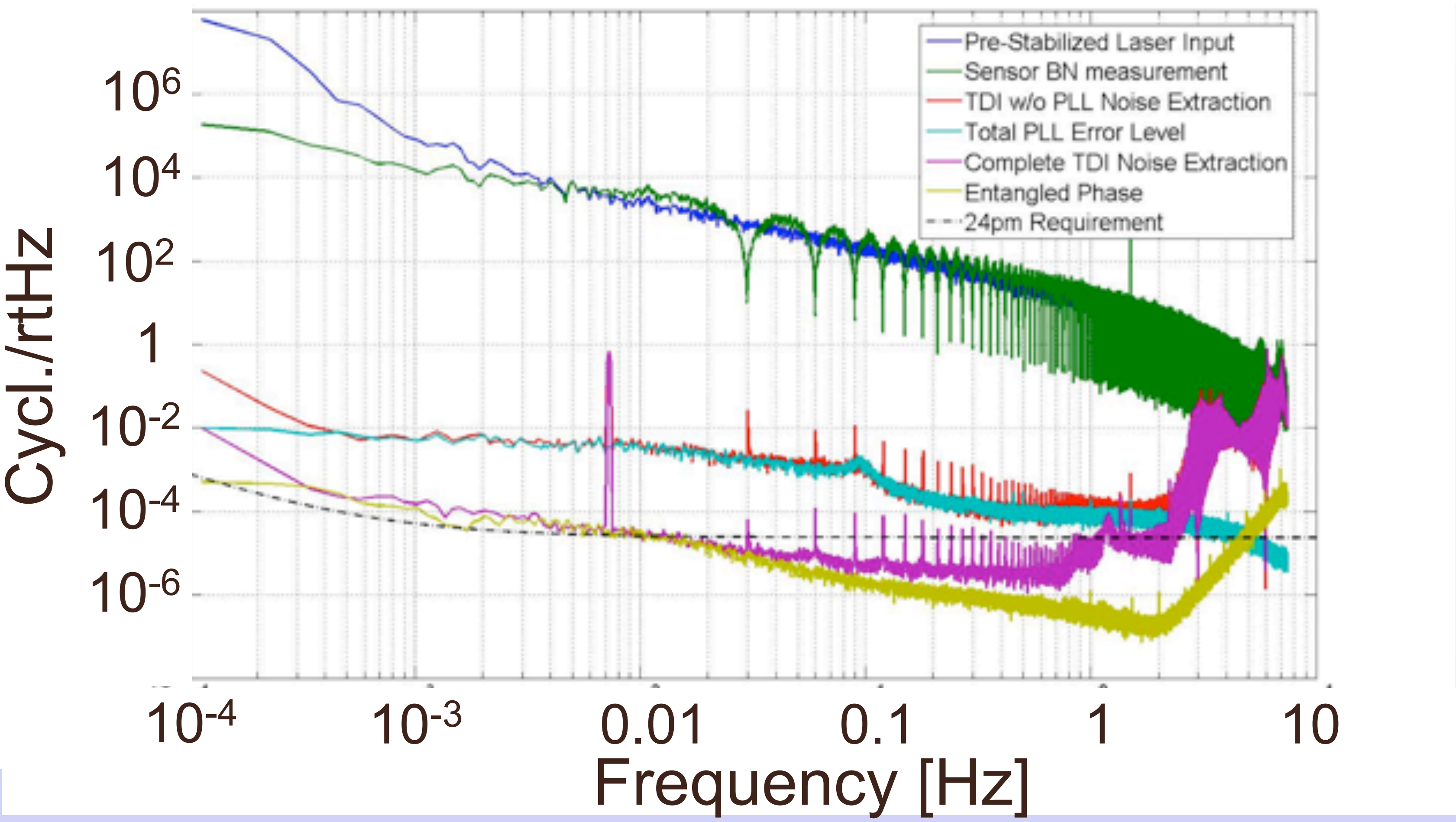
See: Experimental Demonstration of Time-Delay Interferometry for the Laser Interferometer Space Antenna, Glenn de Vine, Brent Ware, Kirk McKenzie, Robert E. Spero, William M. Klipstein, and Daniel A. Shaddock, Phys. Rev. Lett. 104, 211103 (May 2010)

UF Testbed

Generation of
TDI-X Combination with:

- One Laser per S/C
- LISA-like delays
- Doppler shifts
- GW





- Optical PLL's
- Frequency pre-stabilization
- Fractional Delay Filtering
- Ranging with ranging tone at 1.5Hz

Within factor 4 of LISA req.

- Limited by ADC noise
- Use Common Clock

TDI for LISA

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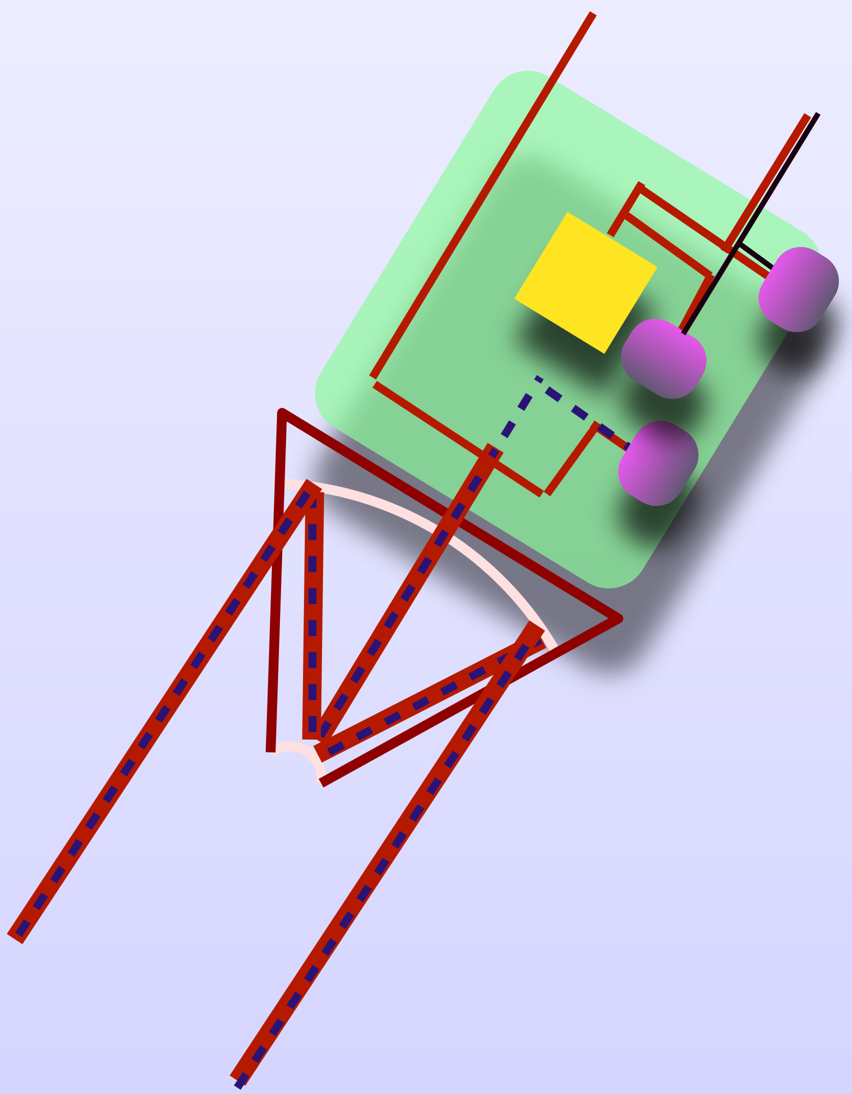
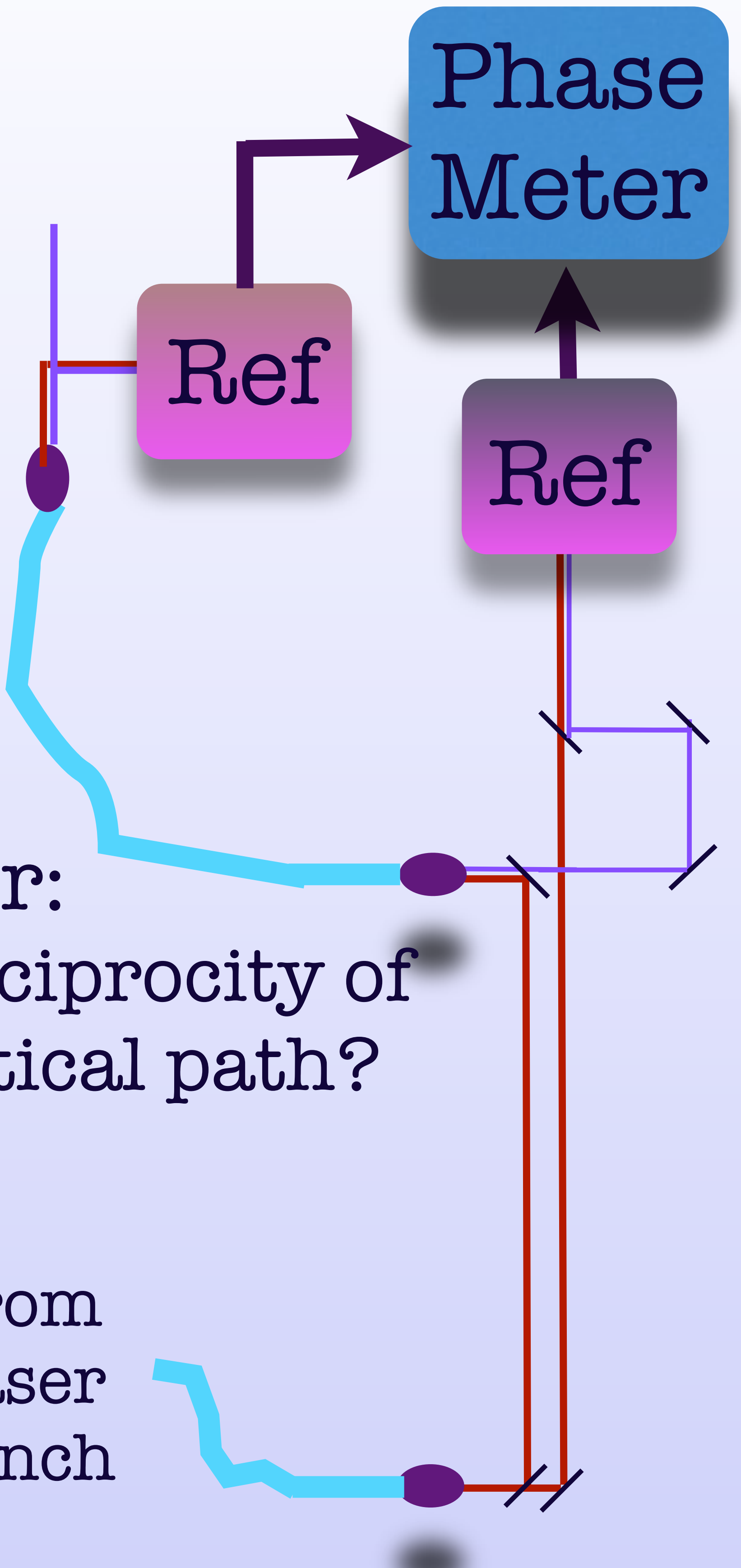


Local Reference Beat

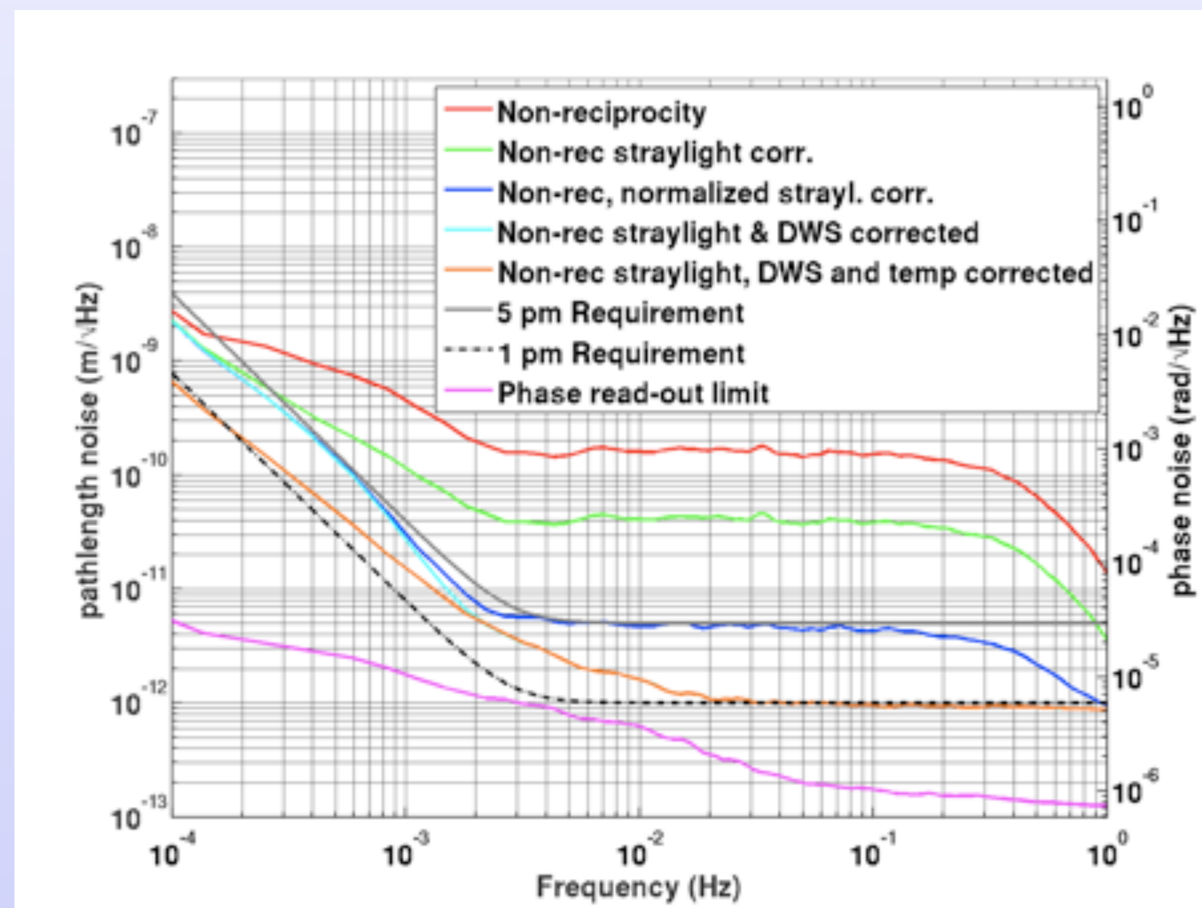


Compares local lasers:

- Laser counter-propagate through fiber
- One Beat Signal on each bench
- Requires reciprocity of fiber

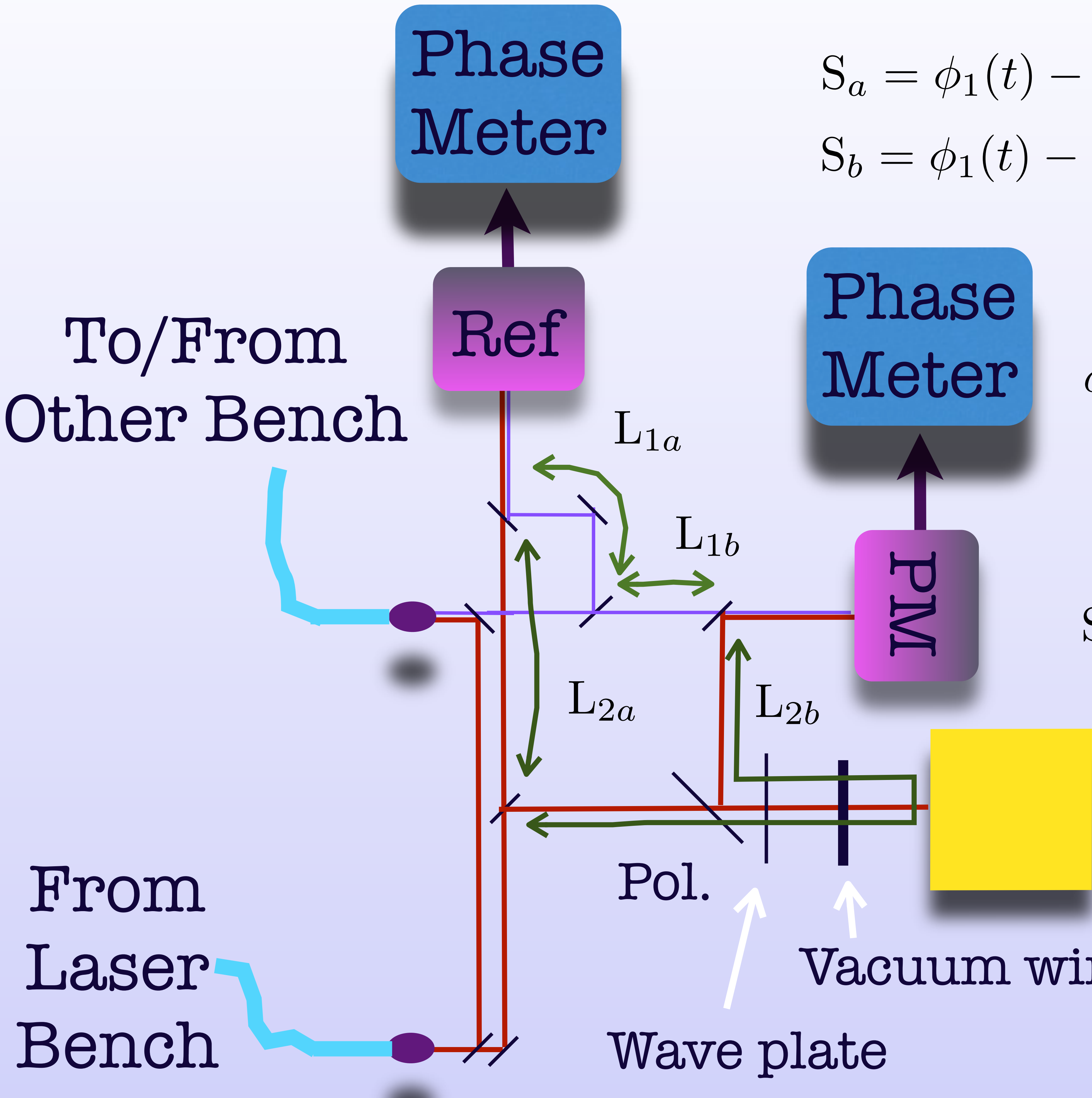
Fiber:

- Reciprocity of optical path?



Courtesy of the Albert Einstein Institute in Hannover

Local Interferometer



$$S_a = \phi_1(t) - \phi_2(t) + \omega_1 \delta L_{1a} - \omega_2 \delta L_{2a}$$

$$S_b = \phi_1(t) - \phi_2(t) + \omega_1 \delta L_{1b} - \omega_2 \delta L_{2b}$$

$$\delta L \begin{cases} < 1 \dfrac{\text{pm}}{\sqrt{\text{Hz}}} & \text{on Bench} \\ \approx 3 \dfrac{\text{nm}}{\sqrt{\text{Hz}}} & \delta L_{2b} \end{cases}$$

$S_a - S_b$: measures changes in Bench to Proof mass distance

TDI for LISA

LISA uses 18+ Signals:

to cancel:

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to generate:

- TDI Comb ons
  - Dep y on PM
  m

Length measurements are under control

3 Types of IFO:

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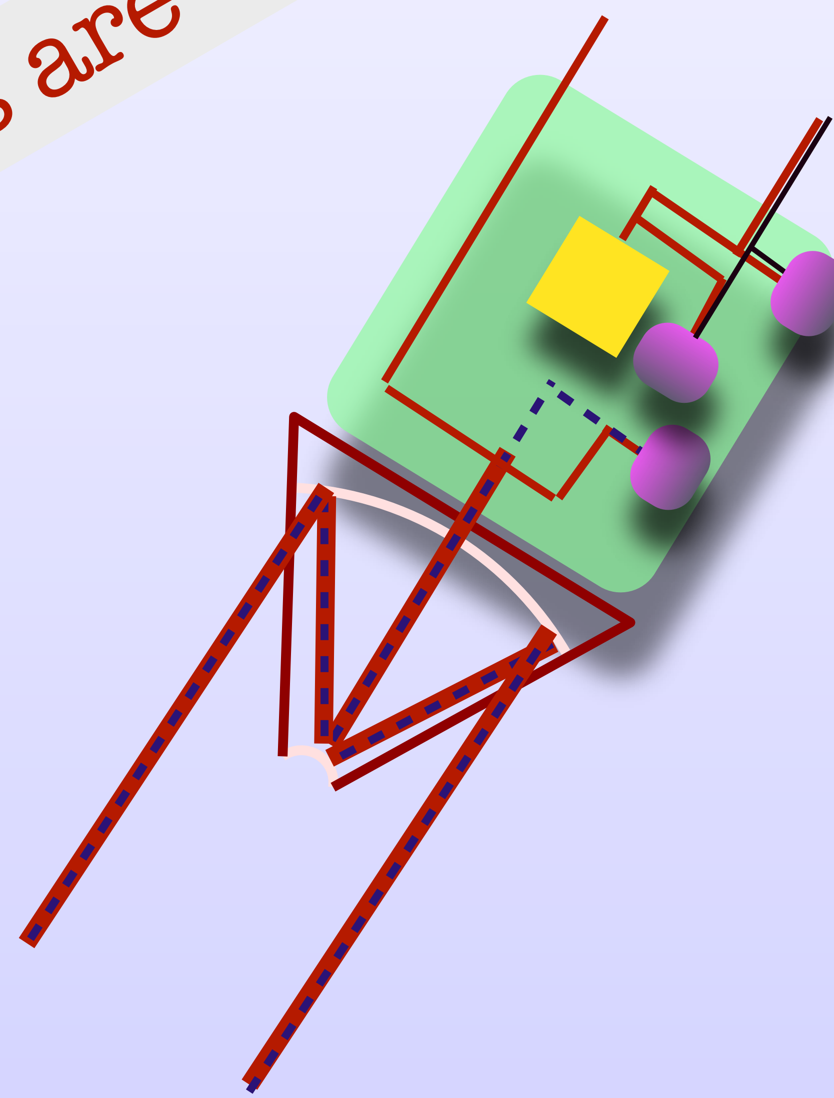
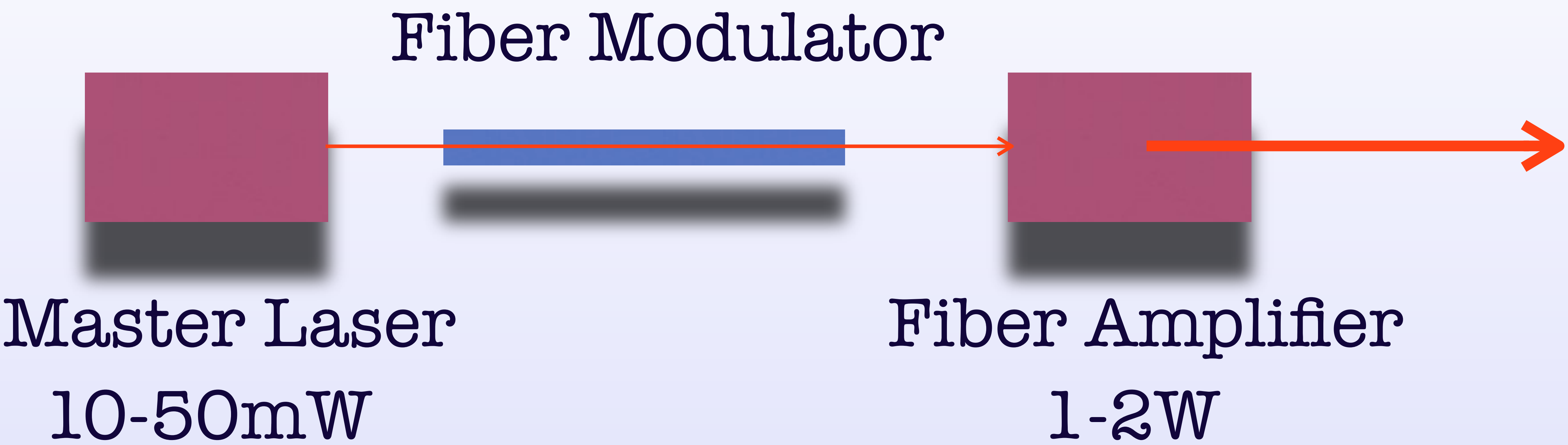


Half of the story ...

Critical Components:

- Lasers
  - Switch board
- Telescopes
- Photo detectors
- Point Ahead Actuator
- ...

Laser Concept



Laser:

- >1W
- Around 1064nm
- Single Frequency
- Single Mode

Challenges:

- Shot noise limited (1mW) @ 2MHz
- Phase fidelity of Ampl.
- Space qualified (Radiation, ...)
- Lifetime

Laser Development

Master laser:

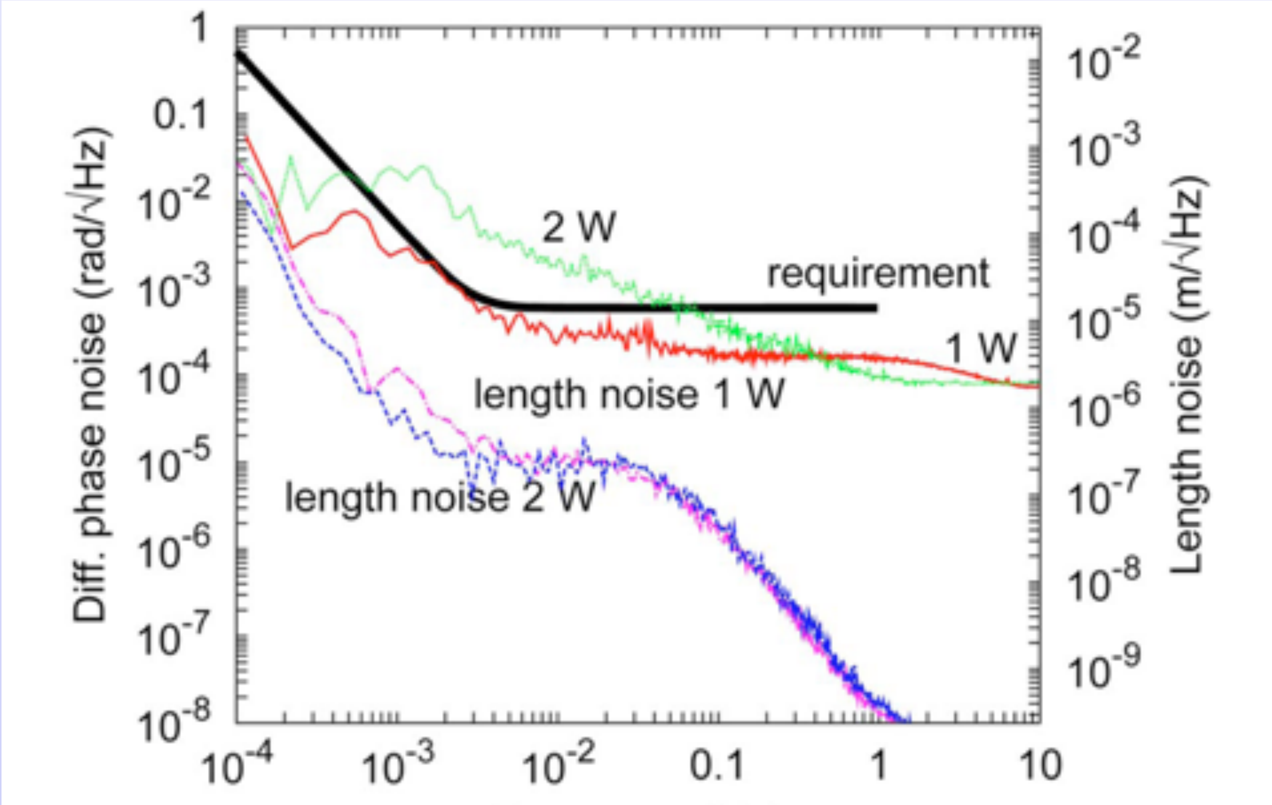
- Tesat laser (LTP)
- Fiber laser
- ECDL

Thermal cycl. of Fiber Laser

Pictures: Courtesy of Kenji Numata, GSFC

Phase Fidelity of Laser Amplifier:

- Initial test results



Pictures: Courtesy of Gerhard Heinzel, AEI

Telescope

- 40cm Diameter
- 60cm Long
- 50nm Wavefront error

2 Concepts:

- On-axis Cassegrain
  - pm/rtHz stability
  - um long term stability
  - Scattered light from Secondary
- Schiefspiegler
  - Off-axis, no direct scattered light
  - Optical truss IFO
  - Refocus mechanism

Telescope requirements similar to Herschel and Silex telescopes

Half of the story ...

Critical Components:

- Lasers
- Telescopes
- Point Ahead Actuator
  - Prototype has been successfully tested
- Photo detectors
  - Experiments started at GSFC and AEI
- ...

Still many optical, mechanical, electrical components need to be tested, but

So far, so good

The End