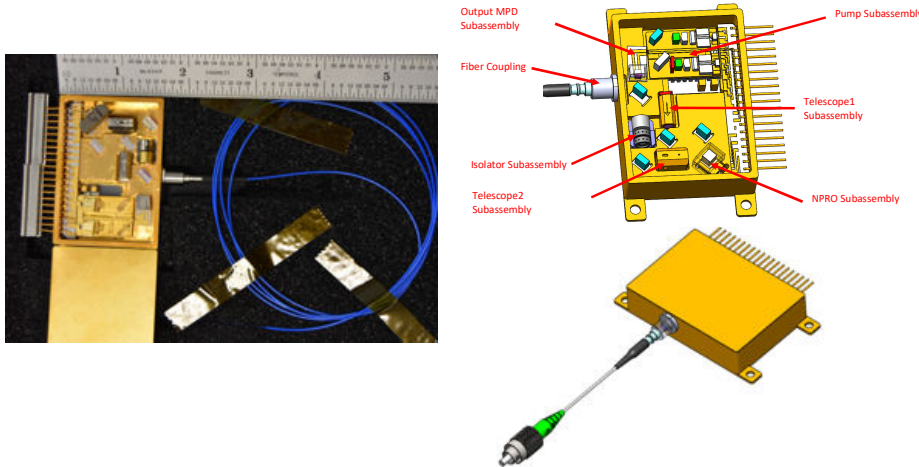


# Technology Quad Chart

## Description with Image



## Instrumentation

- *Low RIN, phase and frequency noise laser transmitter*
- *Applications -*
  - *Precision laser ranging*
  - *Seed laser for narrow linewidth high power/energy laser systems*
  - *Laser spectroscopy*
  - *LRI*

## Programmatics

- *Schedule for mNPRO development*
  - *Phase 2 build in 4<sup>th</sup> Quarter 2019*
  - *TRL4/5 by end of 2019*
  - *TRL6 demonstration by 3<sup>rd</sup> Quarter 2020.*
  - *Lifetest to begin 4<sup>th</sup> Quarter 2020.*

## Scientific and Technical Performance

- *Phase 1 performance of mNPRO matched TESAT laser performance.*
- *Expected Phase 2 will exceed TESAT and met LISA requirements.*



# LRI IMPROVEMENTS FROM LISA

Kenji Numata and Anthony Yu  
NASA Goddard Space Flight Center  
31 July 2019

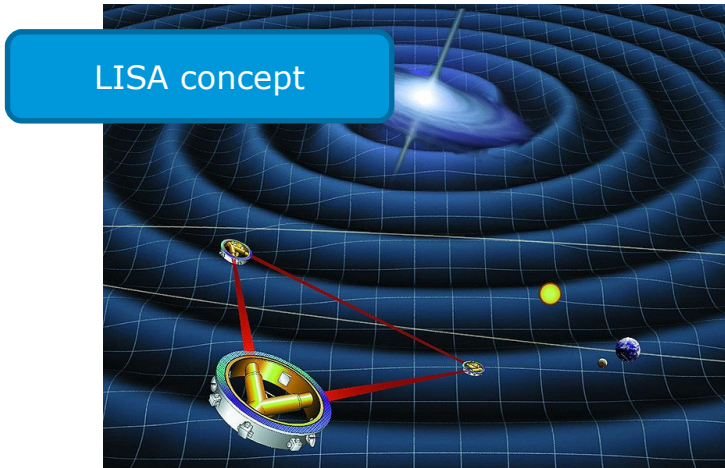
Mass Change Community Workshop  
July 30 - August 1, 2019  
Holiday Inn Washington Capitol, Washington DC

# Gravitational wave detection



- Size of strain  $h$ 
  - $h \sim 10^{-21}$  for typical GW source
  - $L \sim 10^6 \text{ km}$  (LISA):  $L * h \sim 1 \text{ pm}$
- LISA (Laser Interferometer Space Antenna)
  - ESA (European Space Agency)-led mission,  $\sim 2032$  launch
  - Displacement measurement between “free” masses  
Concept validated by the LISA pathfinder mission
  - Laser system  
Candidate US (NASA) component contribution

<http://sci.esa.int/lisa-pathfinder/>





# Top Level Requirements for LISA



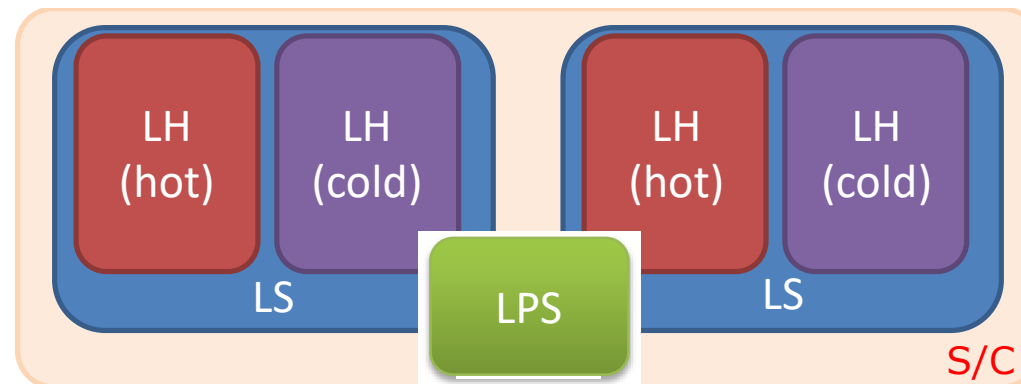
## □ Top level LISA laser requirements

- Wavelength & power  
Wavelength: 1064.49nm, >2W on optical bench at EoL,
- Size & mass  
200 x 200 x 200mm (incl. electronics), 10kg per laser head (LH)
- Lifetime  
1 yr (AIT) + 3-7 yr (on ground, post delivery) + 1.5 yr (cruise) + 1 yr (comm & cal) + 4 yr (science) + 6 yr (extension)
- Noise requirements  
Frequency, intensity, RF phase noise
- Other requirements  
Dissipated power <50W  
OP temperature  $20 \pm 10^\circ\text{C}$   
NOP temperature  $-20^\circ\text{C}$  to  $+50^\circ\text{C}$   
Few mW pick-off for Laser Pre-stabilization System (LPS)  
Linear polarization

## Redundancy



- ❑ Each payload has two laser system (LS) assemblies
  - Each laser system comprises a Laser Optical Module (LOM) and Laser Electrical Module (LEM).
- ❑ Each laser system (LS) contains two Laser Heads (LH)
  - 4 per S/C, 12 in the constellation
  - Cold redundancy
- ❑ One Laser Pre-stabilization System (LPS) per S/C
  - Redundancy at constellation level (3 in the constellation)



# Laser Frequency Noise Requirements

- Free-running frequency stability requirement (for initial phase lock)

$$S_\nu(f) \leq 3.75 \frac{\text{Hz}}{\sqrt{\text{Hz}}} \sqrt{1 + \left(\frac{8 \text{ kHz}}{f}\right)^2} \quad \text{for } 3 \times 10^{-5} \text{ Hz} \leq f \leq 1 \text{ MHz}$$

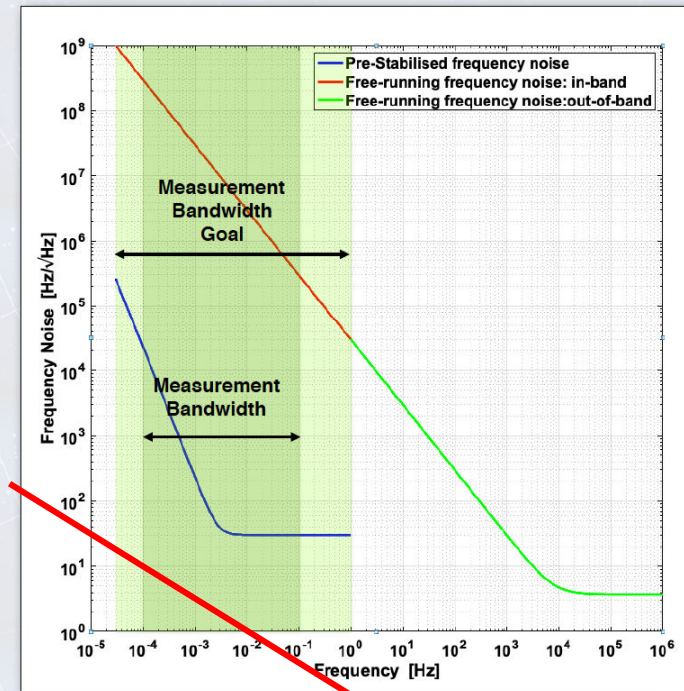
- Pre-stabilised frequency noise requirement (driven by TDI)

$$S_\nu(f) \leq 30 \frac{\text{Hz}}{\sqrt{\text{Hz}}} \sqrt{1 + \left(\frac{2.8 \text{ mHz}}{f}\right)^4} \quad \text{for } 3 \times 10^{-5} \text{ Hz} \leq f \leq 1 \text{ Hz}$$

- Differential phase noise (carrier/sideband)

$$S_\phi(f) \leq 0.6 \frac{\text{mrad}}{\sqrt{\text{Hz}}} \sqrt{1 + \left(\frac{2.8 \text{ mHz}}{f}\right)^4} \quad \text{for } 3 \times 10^{-5} \text{ Hz} \leq f \leq 1 \text{ Hz}$$

- Frequency reproducibility  $\pm 50 \text{ MHz}$  (preferably  $\pm 20 \text{ MHz}$ )

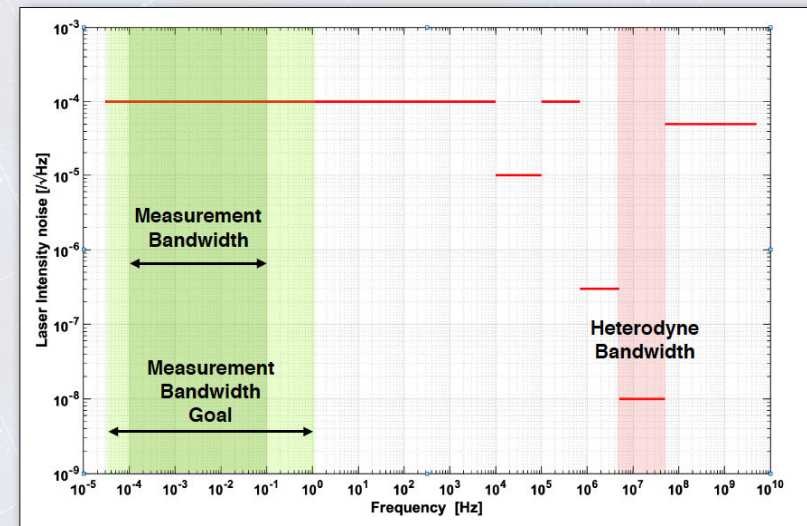


Thermal (Brownian) noise level of typical optical cavity

# RIN Stability Requirements

- ③ Free-running laser relative intensity noise (RIN)
  - Most stringent RIN frequency band is around the heterodyne frequency (tens of MHz)
- ③ Stabilized laser RIN
  - The amplifier output must be stabilized to  $10^{-4}/\sqrt{\text{Hz}}$  level in the measurement band, to minimise radiation pressure noise on the test masses.

$S_{RIN}(f) < 10^{-4}/\sqrt{\text{Hz}}$ $\delta_{ppRIN} < 0.06$	} for $3 \times 10^{-5} \text{ Hz} \leq f \leq 10 \text{ kHz}$
$S_{RIN}(f) < 10^{-5}/\sqrt{\text{Hz}}$ $\delta_{ppRIN} < 0.02$	} for $10 \text{ kHz} \leq f \leq 100 \text{ kHz}$
$S_{RIN}(f) < 10^{-4}/\sqrt{\text{Hz}}$ $\delta_{ppRIN} < 0.02$	} for $100 \text{ kHz} \leq f \leq 700 \text{ kHz}$
$S_{RIN}(f) < 3 \times 10^{-7}/\sqrt{\text{Hz}}$ $\delta_{ppRIN} < 1 \times 10^{-4}$	} for $700 \text{ kHz} \leq f \leq 5 \text{ MHz}$
$S_{RIN}(f) < 10^{-8}/\sqrt{\text{Hz}}$ $\delta_{ppRIN} < 5 \times 10^{-4}$	} for $5 \text{ MHz} \leq f \leq 50 \text{ MHz}$
$S_{RIN}(f) < 5 \times 10^{-5}/\sqrt{\text{Hz}}$	for $50 \text{ MHz} \leq f \leq 5 \text{ GHz}$



Near shot-noise limited performance at the heterodyne frequency band.



# NASA Activities and Objectives



- ❑ To develop and improve the technology readiness level (TRL) of the laser transmitter for the LISA mission to 6.

Tasks	Milestones
TRL4/5 Laser System Engineering Model (EM) Delivery	2/2020
TRL6 Laser System Engineering Test Unit (ETU) Delivery	7/2021
TRL6 Laser System ETU Lifetest	Implement at various development stages

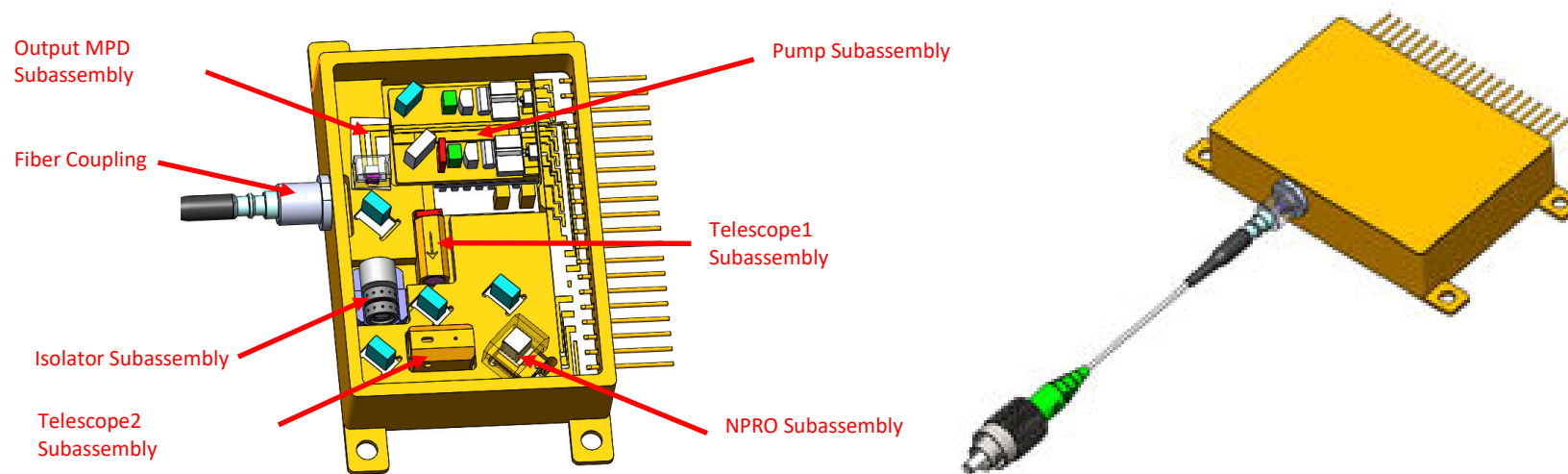
- ❑ Significance of Work:
  - Develop enabling technology for the LISA mission
  - US contribution to the LISA mission led by ESA
- ❑ Approach:
  - MOPA laser architecture that is consistent with the ESA approach for LISA
  - Develop two MO approaches for risk mitigation
  - Similar parallel approach for the PA development
  - Integrate MO and PA to demonstrate MOPA performance meeting LISA's requirement.
  - Develop and implement reliability test plan on critical components and systems.



# MICRO-NON PLANAR RING OSCILLATOR (m-NPRO)

# Overview of m-NPRO laser development

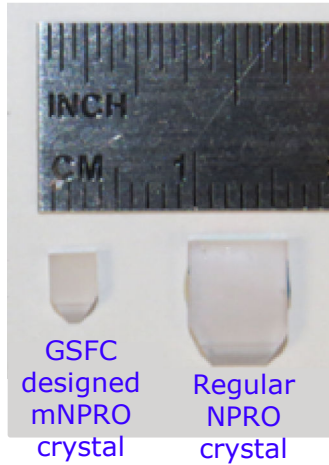
- Micro-NPRO with short cavity length
  - Main objective is to reduce for factor with low size, weight and power (SWaP) packaging approach
  - Allows for full redundancy of the seed laser in the laser head to meet the LISA lifetime requirement
  - Additional benefit is to extended longitudinal mode spacing
  - Large Free Spectral Range (FSR) of  $\sim 30\text{GHz}$
  - Standard NPRO has FSR of  $8\text{GHz}$



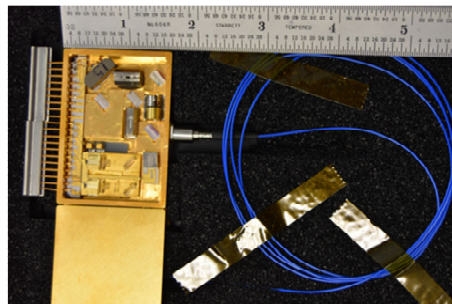
Dimensions: 70 mm (2.75") x 45 mm (1.75") x 15 mm (5/8")

# Comparisons of mNPRO to NPRO Lasers

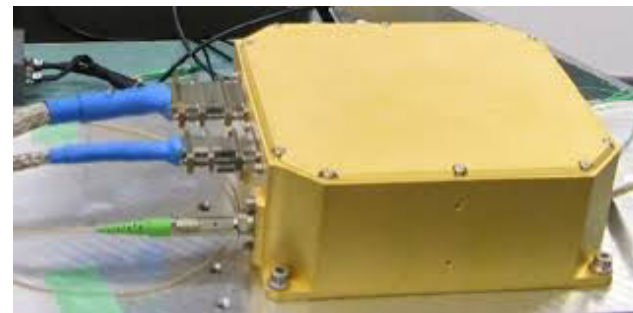
\*\* Used in Lightwave NPRO, and standard TESAT. GFO version of crystal is even larger.



GSFC mNPRO



TESAT NPRO



*These images are to scale.*

# Specifications for Packaged m-NPRO MO

Parameter	Unit	Min	Typ	Max
<b>Output Laser</b>				
Wavelength	nm		1064	
Mode		TEM00		
Power	mW	150		
Fiber Type		PM980		
Output PER	dB		15	
Polarization Orientation		Fiber Slow Axis		
Fiber Coupling	%	50		
Fiber Facet Angle	°		8	
Fiber Connector		FC/APC		
Fiber Jacket Material		Hytrel		
Fiber Length	m	TBD		
Monitor Photodiode		Required		

<b>Package</b>				
Size	mm	<(70x45x35)		
Hermetic		Yes		
Shielding		TBD		
Mounting		TBD		

<b>Environmental</b>				
Base Temperature	°C	TBD		
Shock		TBD		
Vibration		TBD		

Parameter	Unit	Min	Typ	Max
<b>NPRO Subassembly</b>				
Material		Nd:YAG		
Entry Facet Coating		AR @808 / HR 95-99% @1064		
PZT Thickness	mm		0.5	
PZT Square Dimension	mm		4	
PZT Voltage				100
Magnet Direction		H-vector along crystal length		
Temperature Control	°C		0.1	
NPRO ROC	mm		100	
NPRO Dimensions	mm	4.499x3.0x1.2		

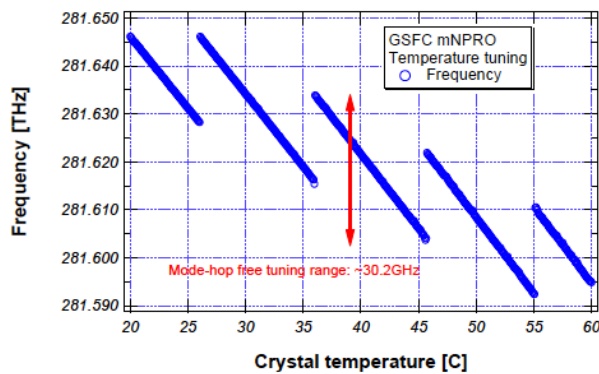
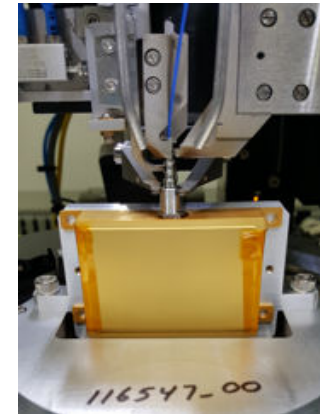
<b>Pump Laser</b>				
Wavelength	nm		808	
Mode		TEM00, SLM Preferred		
Power	mW	500		
Temperature Control	°C		1	
Monitor Photodiode		Preferred		

<b>Optical Assembly</b>				
Optical Material		Fused Silica, Sapphire, Rad Hard SF6		
Isolation	dB		30	
Isolator Loss	dB			2
Isolator Power	mW	300		

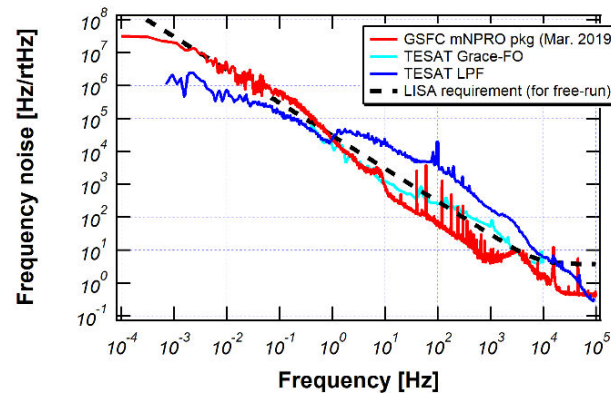
# Master Oscillator (MO)



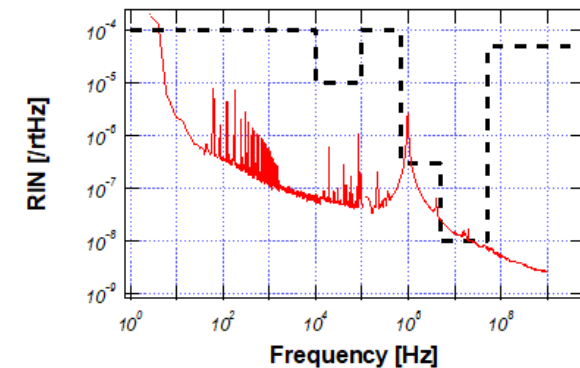
- Phase 1 mNPRO development completed with 4 packaged oscillators
  - Evaluated performance at GSFC
    - Frequency noise, RIN, beam profiles, temperature effects, component loss etc.
- Phase 2 mNPRO in progress to address Phase 1 issues
  - Low output power in fiber ( $\sim 120\text{mW}$  : should be  $\sim 300\text{mW}$  - improving)
  - RIN: factor  $\sim x2$  off from the requirement at 5MHz
    - Same as (or better than) other NPROs. Revisiting the RIN requirement.



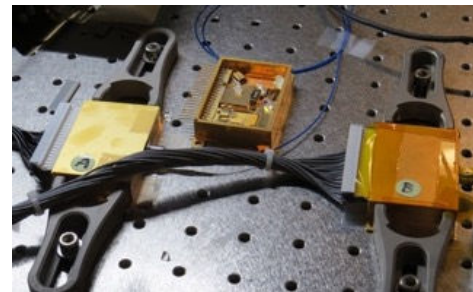
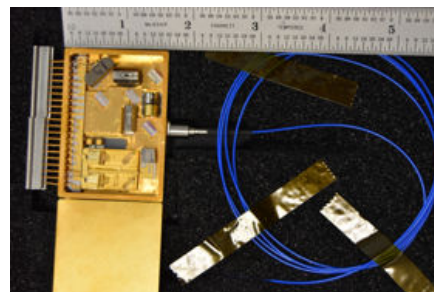
>30 GHz Mode-Hop Free Tuning of packaged mNPRO



Frequency noise of packaged mNPRO



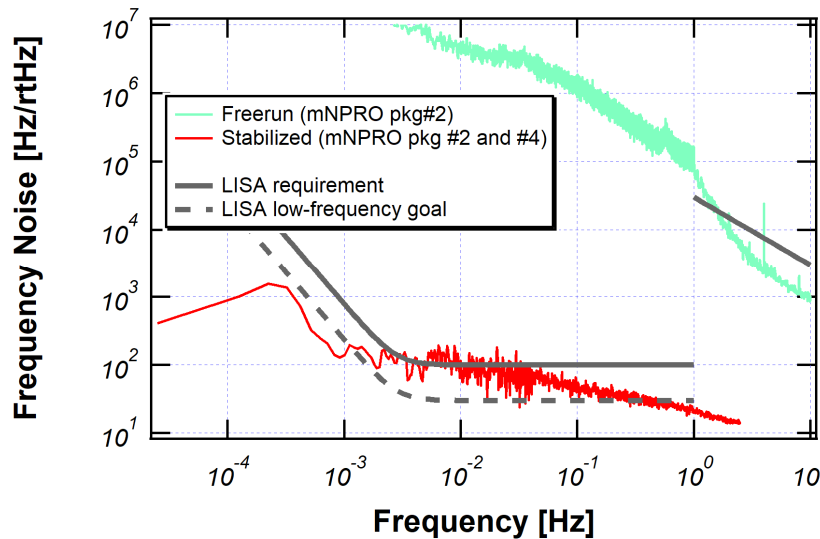
RIN of packaged mNPRO



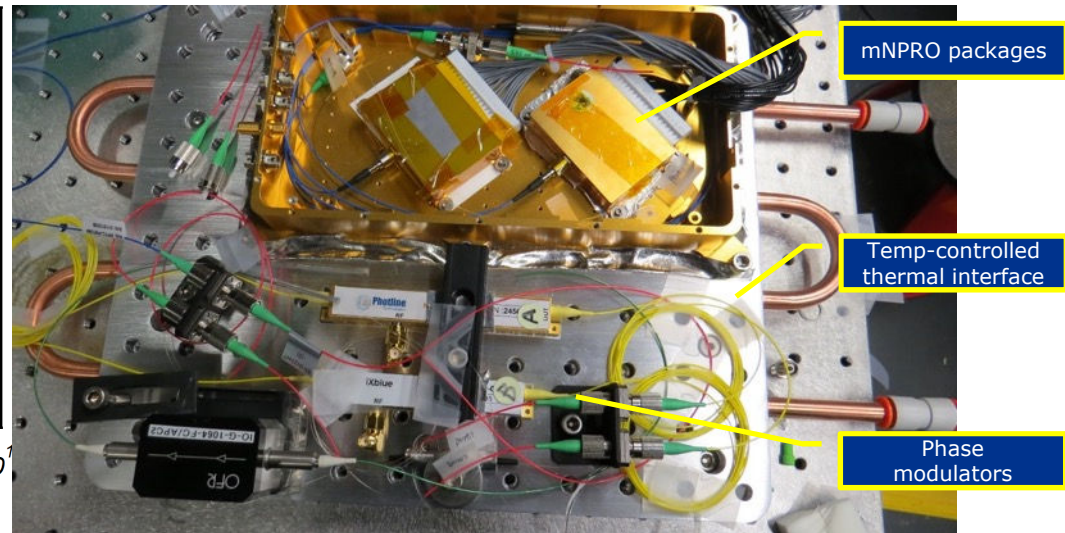
# mNPRO Stabilized Frequency Noise Performance

- Stabilized frequency noise at low Fourier frequency
  - Evaluation with one vertical reference cavity (to exclude noise from the cavity itself)
  - The mNPRO package has been proven to reach the 100Hz/rtHz requirement.

Still improving the test setup to get closer to the “LISA goal” of 30Hz/rtHz as possible.

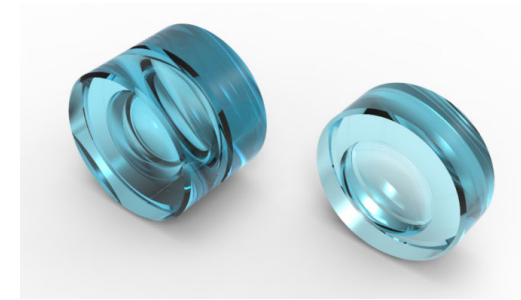


Cavity-stabilized mNPRO frequency noise performance



mNPRO laser source for the cavity stabilization demo (LISA's MO will look similar.)

# Cavity improvement ideas



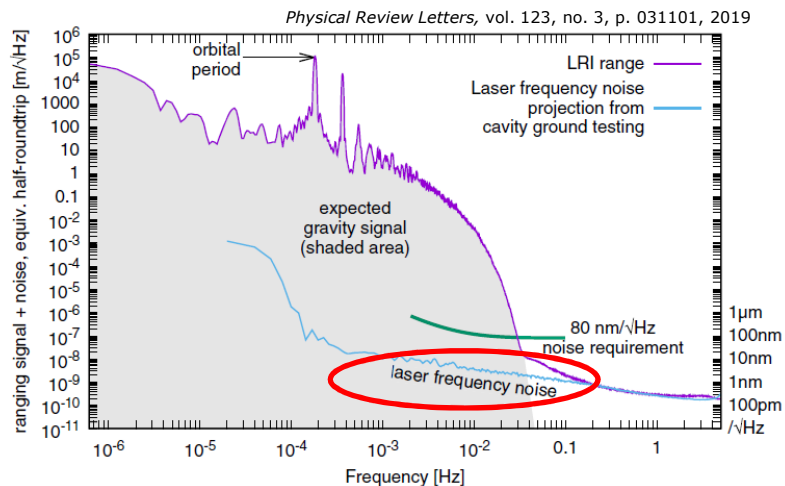
## Lowering thermal noise

### E.g. by Crystalline coatings

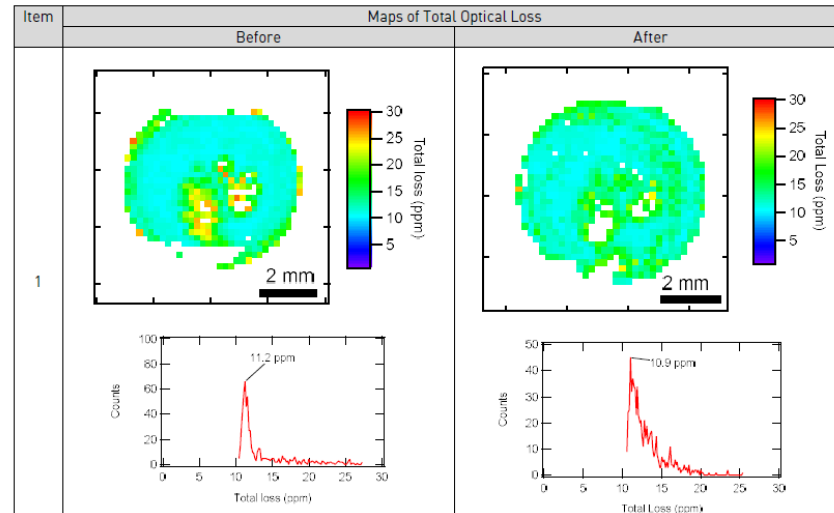
- Gamma-radiation tested as a part of LISA component tests
- Factor  $\sim 3$  (10) reduction expected (in spectrum) at 300K (10K)
- Cavity length can be reduced by  $\sim 3$  (10) times for the same frequency noise requirement.

## Relaxed requirement

- Further reduction of cavity length. Simplified thermal shields.
- Reduces mass, cost,



GRACE FO LRI performance



Gamma effects on crystalline coatings



## Summary



- GSFC is developing a master oscillator power amplifier laser system for the LISA mission.
- The master oscillator is a custom designed micro NPRO -
  - ❑ Reduced size, weight and power with improved performance compared to previous NPRO lasers used in Grace-FO and LISA PathFinder.
  - ❑ Larger free-spectral-range (FSR)
    - Wider mode-hop-free tuning range (more robust)
  - ❑ Smaller mass & small piezoelectric actuator
    - Wider frequency-tuning bandwidth (better in-loop noise suppression)
    - More efficient tuning (larger tuning per voltage)
  - ❑ Smaller package possible
    - Use of telecom packaging technology
    - Possible to have extra redundancy for the given volume
    - **Suited for small satellite platforms**
  - ❑ Need for smaller cavity in future LRI instrument
    - Have ideas for improvement
- Our schedule for the mNPRO and the MOPA laser for LISA is
  - TRL 5 by February 2020
  - TRL 6 by February 2021