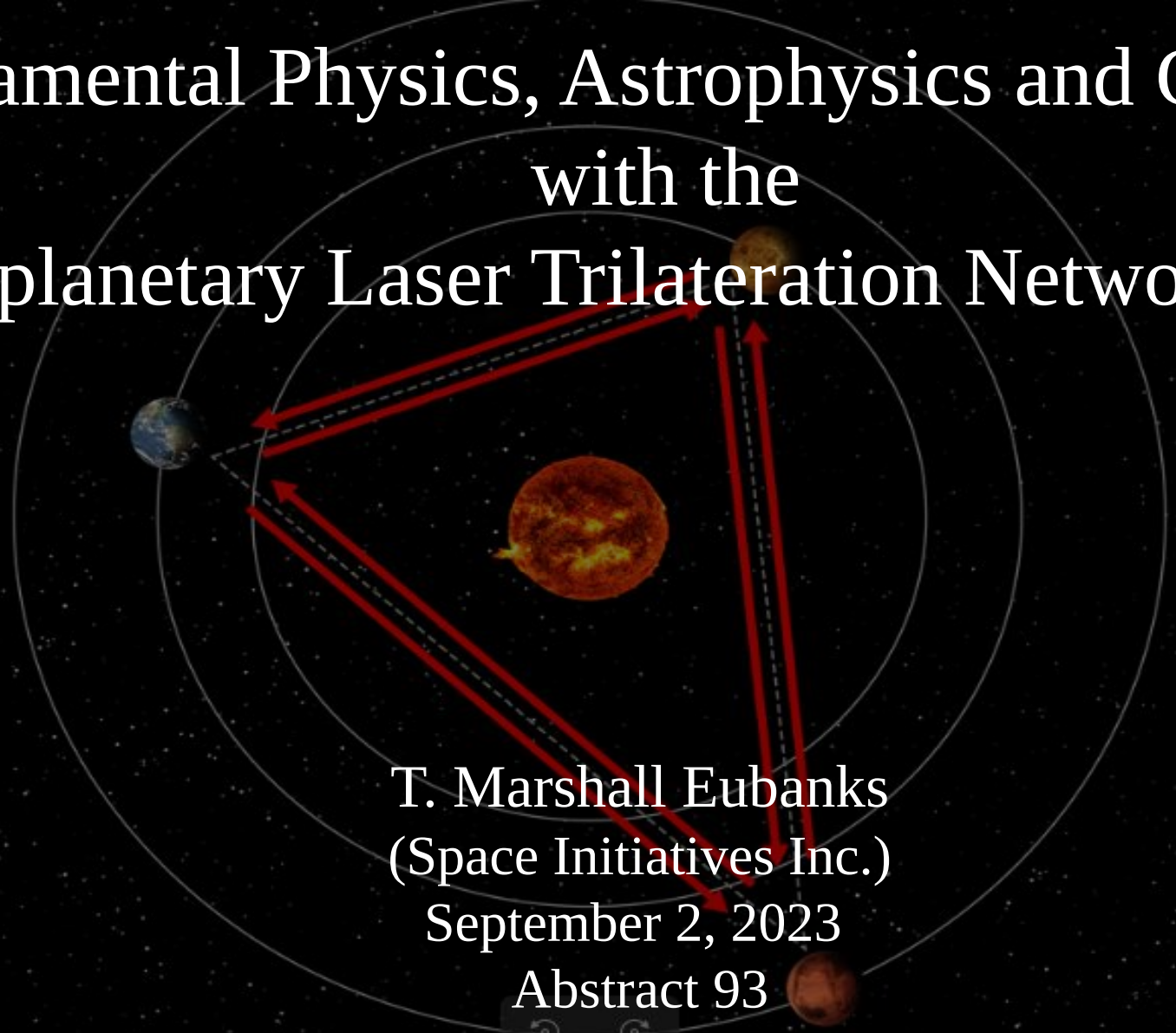


Fundamental Physics, Astrophysics and Cosmology with the Interplanetary Laser Trilateration Network (ILTN)

A diagram illustrating the Interplanetary Laser Trilateration Network (ILTN). It shows the Earth on the left, the Moon in the center, and Mars at the bottom right. Three red double-headed arrows represent laser links forming a triangle between the Earth, the Moon, and Mars. Dashed lines also connect the Earth to the Moon and the Moon to Mars. The background features concentric elliptical orbits and a starry space.

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(Space Initiatives Inc.)
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Abstract 93

The W. M. Keck Institute for Space Studies (KISS) ILTN Workshop
was held at CalTech near here from September 22 to 26, 2025.



The current proposal is based on this workshop.

The Interplanetary Laser Trilateration Network (ILTN)

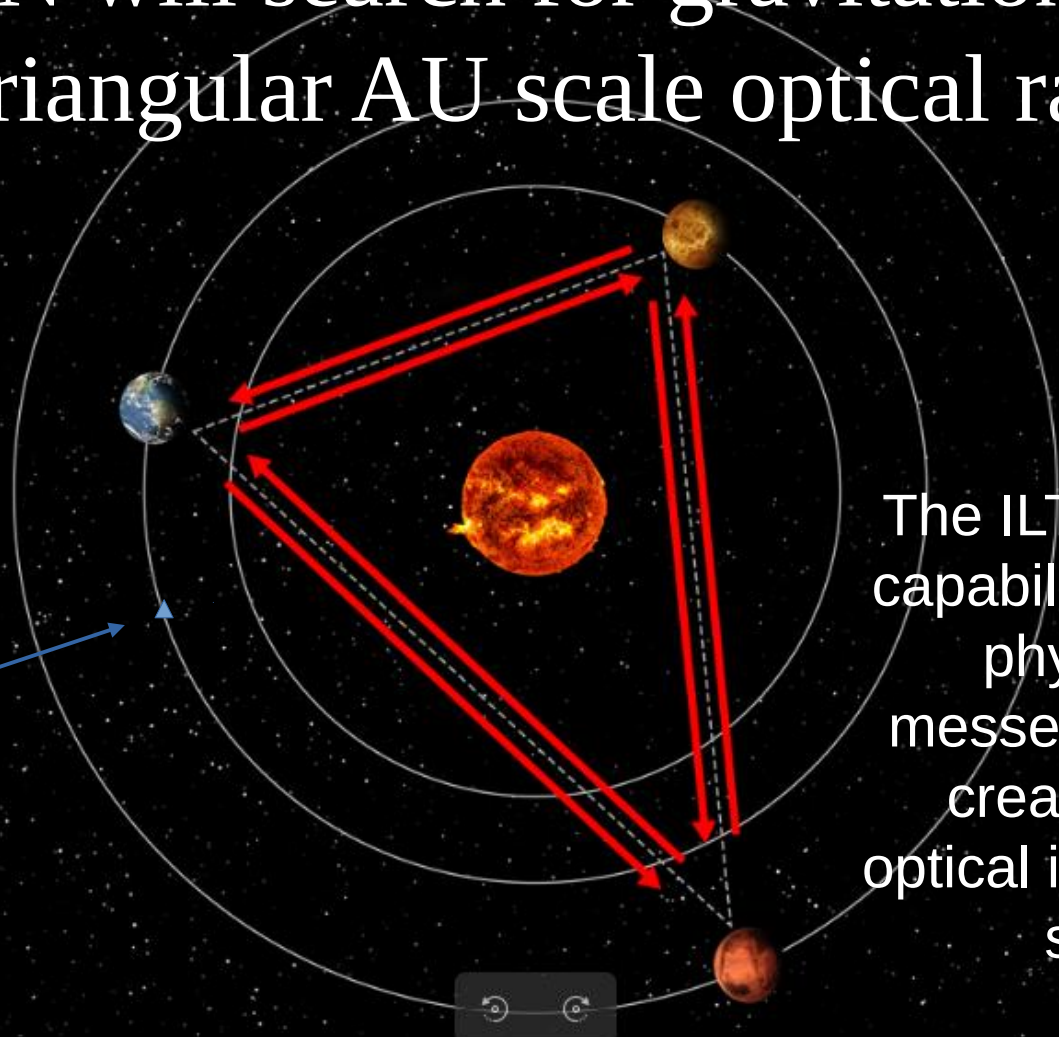
- The ILTN will enable orders of magnitude improvement in the metrology of the inner solar system by providing laser range and phase measurements over interplanetary distances.
 - The ILTN will use the Earth, Mars and Venus to provide “drag free” Inertial Reference Points (IRP) down to nanoHz frequencies.
- The ILTN will enable, between micro and nano Hertz frequencies (periods of a few days to years) observation of gravitational waves (GW) produced by supermassive black hole (SMBH) binaries.
 - This will fill a spectral gap between LISA and the Pulsar Timing Arrays (PTAs).
- The ILTN will form a ring laser gyroscope ~ten orders of magnitude larger than current RLGs.
 - This will provide a direct ability to check the net rotation of the VLBI / Gaia ICRF.
- By operating across the solar system, the ILTN will also provide information about the Sun's deep interior and orders of magnitude improvement in solar system constraints on gravitational theory.

ILTN Science (1)
Gravitational radiation and supermassive
black hole binaries.

The ILTN will search for gravitational waves with triangular AU scale optical ranging.

LISA triangle
(to scale)

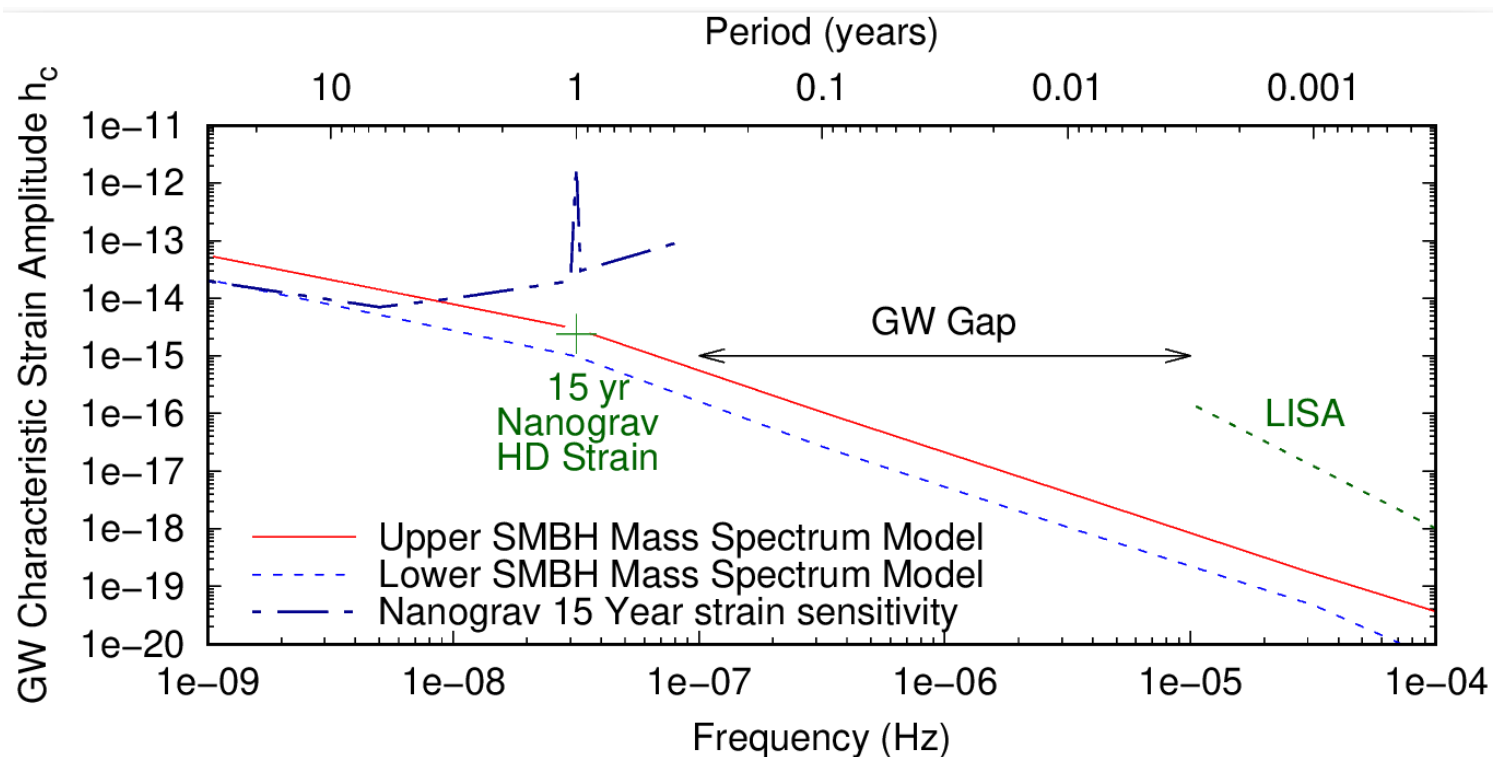
The ILTN will provide new capabilities in fundamental physics and multi-messenger astronomy by creating an AU-scale optical interferometer in the solar system.



Super Massive Black Hole Binaries: A New Era of Gravitational Wave Astronomy

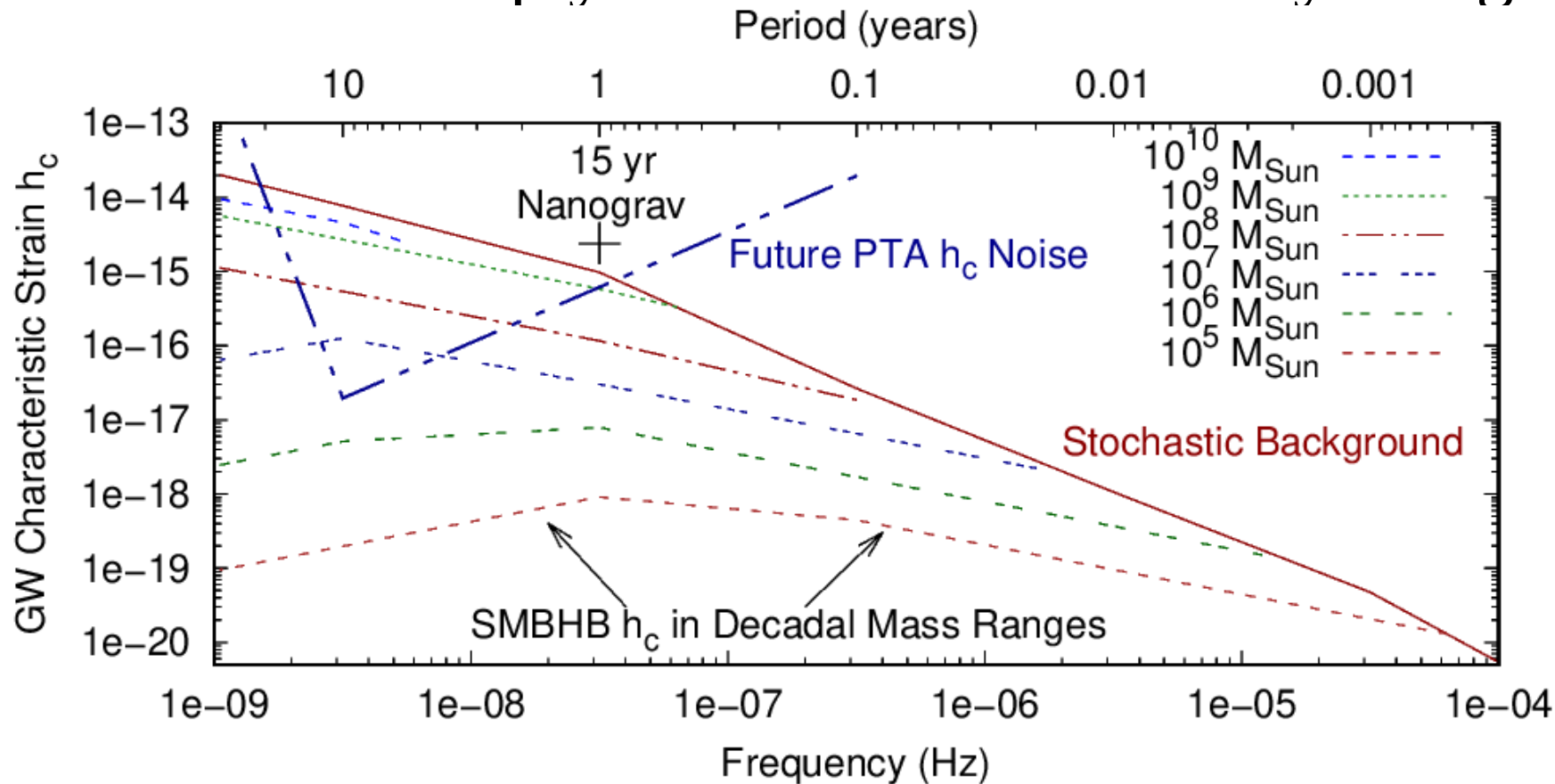
- Significant evidence exists for a stochastic background of “nanoHertz” gravitational waves (GWs)
 - The Nanograv 15-year Pulsar Timing Array (PTA) GW strain estimate is 2.4×10^{-15} at a period of 1 year (Agazie et al. 2023).
 - (The dominant periods are almost certainly longer.)
 - If (as is generally expected) the stochastic GW background is due to SMBH binaries, it should be dominated by very massive (order $10^9 M_{\text{Sun}}$) binaries.
- The next fundamental advance will be the detection of *individual* SMBH Binaries evolving towards merger.
- The ILTN will meet this challenge.

There is a good agreement between the predicted Super Massive Black Hole (SMBH) Binary GW strain and the recently observed Pulsar Timing Array (PTA) strain estimate [Agazie et al, 2023 a and b].



The PTA result is an average over a wide frequency band (roughly, 0.5 to 10 year periods); it is scaled to 1 year purely by convention.

The PTA data imply massive SMBH Binary Mergers



The PTA data imply there are giga-solar mass binaries nearing merger. The ILTN can separate the closer of these sources from the background!

Gravitational Waves: Short versus Long Baselines

- The basic equation for the GW frequency shift, from Estabrook and Wahlquist [1975].

$$\frac{\nu_1 - \nu_0}{\nu_0} = \frac{1}{2} (1 + \cos \theta) [h \cos(\omega t + \phi) - h \cos(\omega (t + (1 - \cos \theta) \tau) + \phi)] \cos 2\psi$$

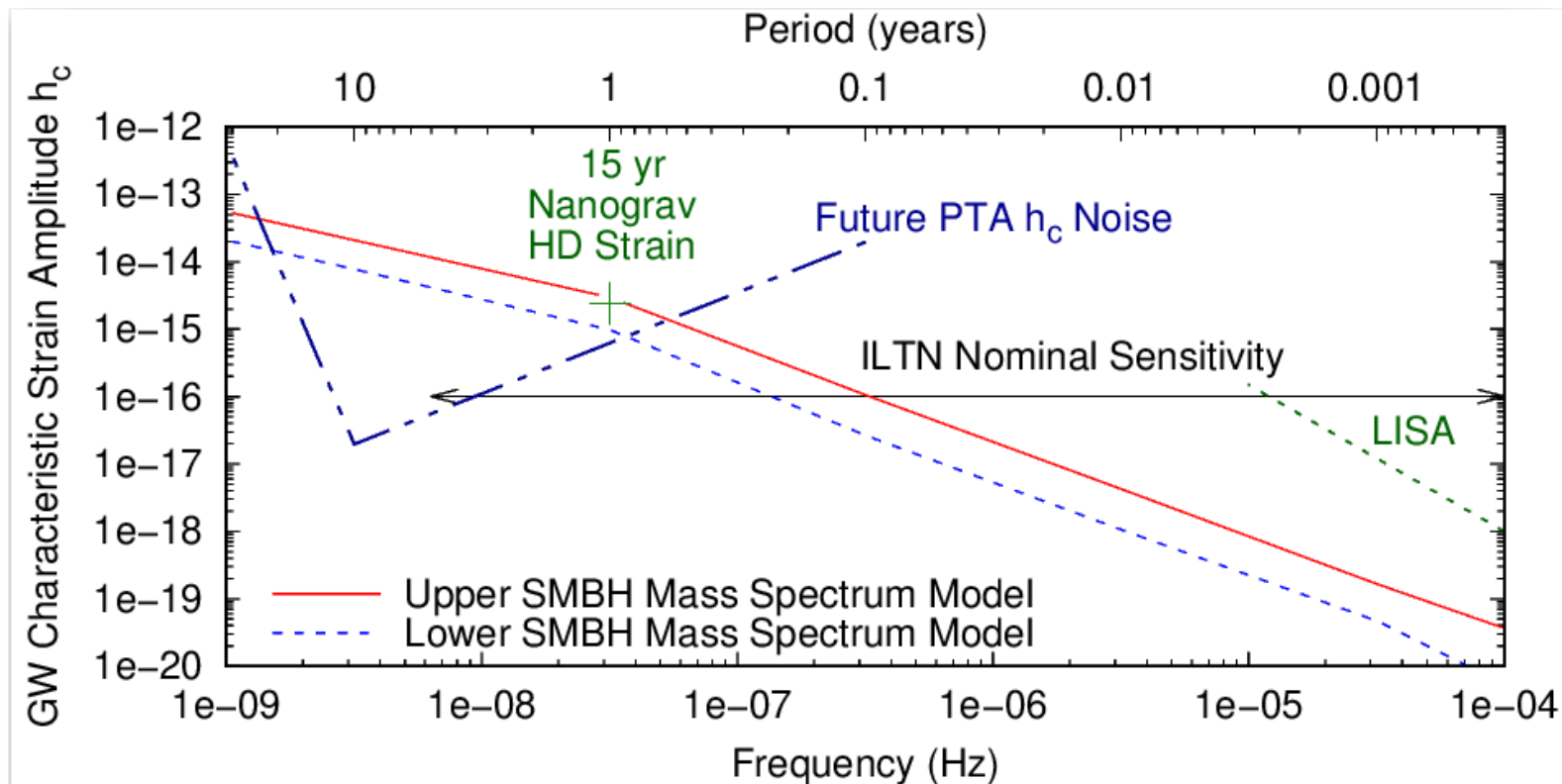
where ν is the photon frequency, h , ω and ϕ are the GW wave strain, frequency, and phase, θ is the angle between the GW source and the remote probe as seen from the emitting probe, with $\cos(\theta) = \alpha$ henceforth, τ is the distance, in light seconds, between the emitter and receiver of photons, ϕ is an arbitrary phase angle, and ψ the horizontal polarization angle of the GW (this term is ignored henceforth).

- There are two useful approximation regimes, **short baseline**, where $\omega \tau (1 - \alpha) \ll 1$, and **long baseline**, where $\omega \tau (1 - \alpha) \gg 1$.
- The PTAs operate in the long baseline regime, where the GW signal does not scale with τ but the time delay (the time integral of $\Delta\nu$) does scale as $(\frac{1}{\omega})$.
- The ILTN will operate in the short baseline regime, where

$$\frac{\nu_1 - \nu_0}{\nu_0} = \frac{1}{2} (1 + \alpha) h [(1 - \alpha) \omega \tau] \times \sin(\omega t + \phi)$$

and so the two ω terms cancel in the time integral, yielding a GW delay that is $\propto$ the strain times the baseline delay.

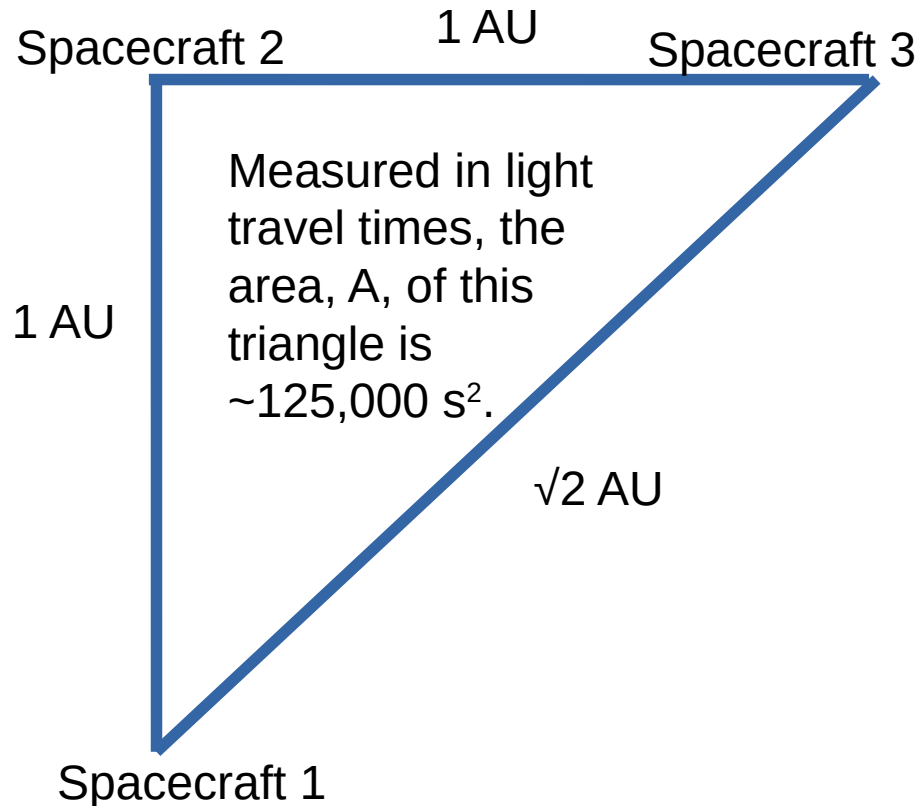
The ILTN will fill the PTA/LISA spectral gap



With their different baseline regimes, even with a 5 year nominal ILTN mission, the PTA and the ILTN will complement each other,

ILTN Science (2)
Cosmological Rotation with
the Sagnac Effect

The ILTN will provide the means verify the rotational stability of the International Celestial Reference Frame (ICRF).



- The Sagnac observable (the time difference of two opposing passages around the triangle) provides
 - $\Delta T = 4 A \omega$,
 - Where A is the area and ω is the net orthogonal rotation rate.
- Assuming we can determine ΔT to 0.1 picosecond , we can determine ω to $\sim 2 \times 10^{-19}$ radians / s *on a hourly basis*.
 - Or $\sim 1.3 \mu\text{as} / \text{year}$, better than the (decades long) VLBI ICRF3 average using quasars.

ILTN Science (3)

Fundamental Gravitational Physics

The ILTN and Solar System Relativity

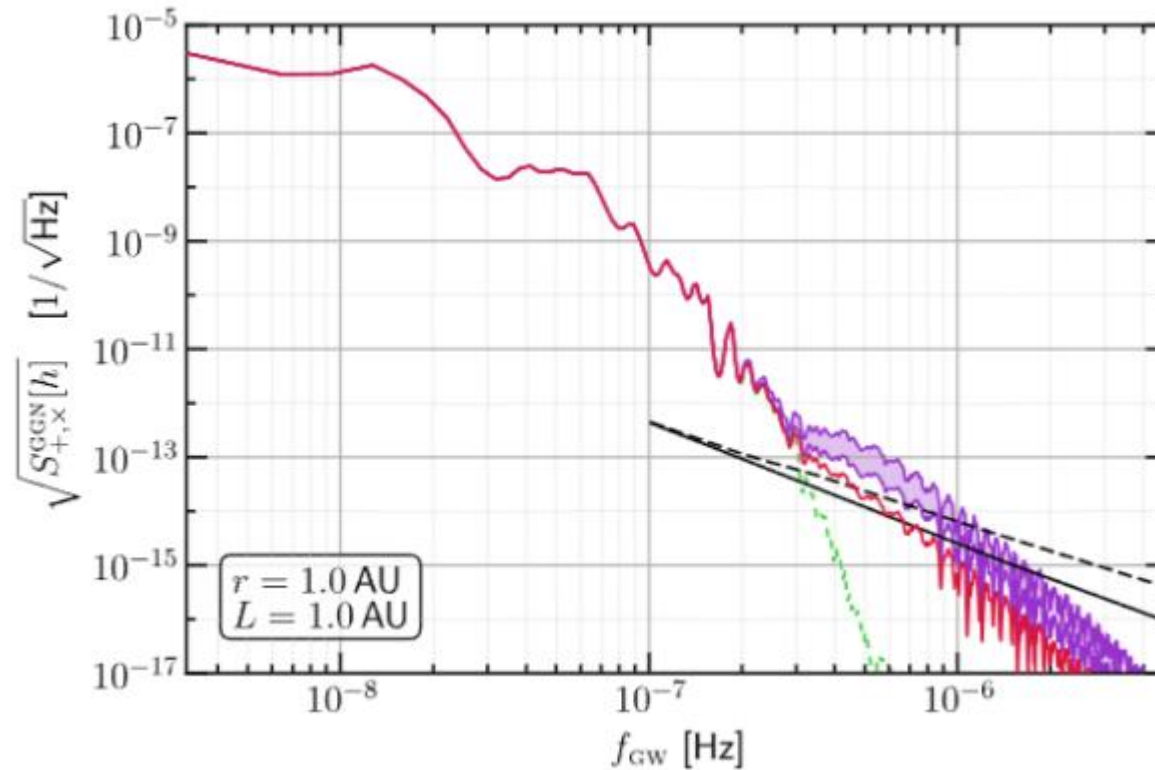
- The ILTN will enable a variety of precision tests of General Relativity and other theories of gravity in the solar system.
- 1.) Parameterized Post-Newtonian (PPN) constraints.
 - The best constraint on PPN γ is currently Cassini, with $\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$.
 - The ILTN should be able to do ~ 3 orders of magnitude better with this and similarly improve Nordtvedt effect and β determination tests.
- 2.) The ILTN should be able to directly detect the Lense-Thirring perihelion precession of Venus, Earth and Mars ($\sim 30 \mu\text{as yr}^{-1}$).

What does the ILTN Need?

ILTN Critical Technology Needs

- ILTN has critical technology needs in both laser metrology and spacecraft clock technology.
 - There was considerable debate, but no consensus, at the KISS workshop about continuous wave phase tracking versus pulsed laser ranging (and also hybrid modulated continuous wave systems). This needs serious design study work.
- The ILTN needs phase coherence at the 10^{-16} level over 1000 second intervals. This can be done through frequency phase transfer, optical-frequency division or comb-based references, ultra-stable lasers, inter-spacecraft time transfer, and simultaneous lower-frequency calibration bands.
 - All of these will need development for ILTN space operations.

We Need to Get Serious about Asteroid Noise



Simulated asteroid gravity gradient noise (GGN) between the two ends of a GW detector of length 1AU located at 1AU from the Sun (from Fedderke et al. (2021)). The strain at low frequencies is considerably larger than the expected GW strain.

The ILTN And Asteroid Noise

- *Asteroid noise will be a problem for **all** AU-scale short baseline GW observatories.*
- However, it is different from most other astronomical noise sources:
 - If we knew the mass of every asteroid we could remove this noise perfectly.
 - For any given asteroid we can predict its perturbation, and how that differs from the GW signatures.
- We will develop Time Delay Interferometry (TDI) and least squares techniques to separate GW and asteroid perturbations in ILTN data processing.
 - The ILTN will be a powerful tool to determine asteroid masses.
- At the same time, there needs to be a wider concerted effort to determine asteroid masses.

ILTN Design Study Needs

- The proposed Ad ASTRA study should retire three major challenges
 - Exploration of orbital configurations that deliver the best drag free inertial reference points and operational performance.
 - Determine the best laser and clock systems for measurements over AU-scale separations, and in particular whether the ILTN should use laser pulse or laser phase measurements
 - Determine how astrometry, occultation measurements and time delay interferometry (TDI) can best control gravitational perturbations from asteroids.

Conclusions

- The combination of ILTN, LISA and PTA data will help in the finding of relatively near individual SMBH binary sources, thus addressing the "Discovery Area" B-DA in the 2020 Astrophysical Decadal Survey, *"Transforming our view of the universe by combining new information from light, particles and gravitational waves."*
- The proposed ASTRA study should retire three major challenges, but the ILTN badly needs a simulations on every aspect of its performance.
- The ILTN also needs an examination of the benefits of providing PNT support in cislunar space through LunaNet and at Mars through the Artemis/Moon-to-Mars program.