Bridging the μHz gap with asteroids

The XXVIII International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2021)

Remote presentation

August 27, 2021

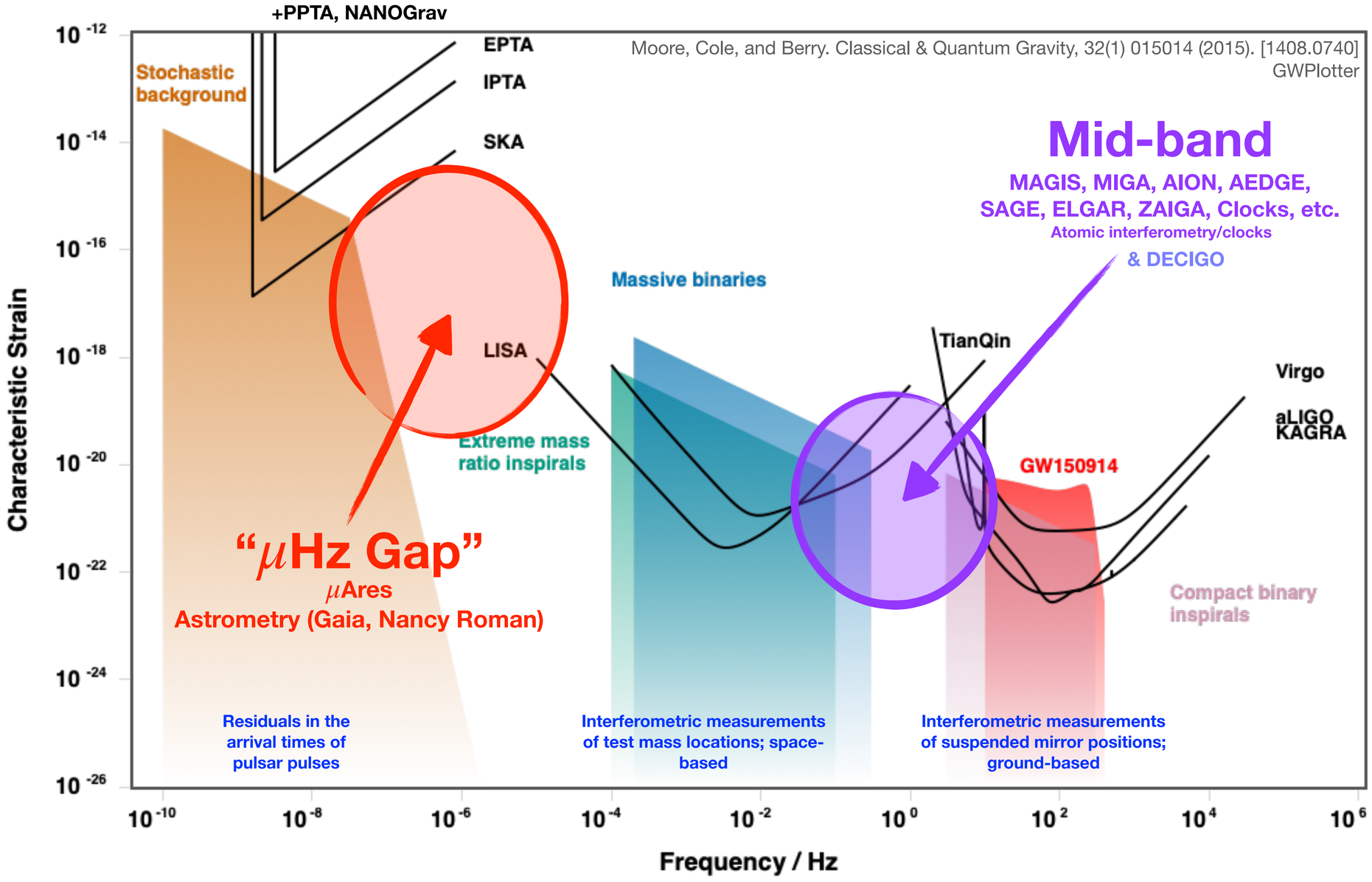
M.A.F., P.W. Graham, and S. Rajendran. *In preparation* (2021). [21xx.yyyyy].
M.A.F., P.W. Graham, and S. Rajendran. *Phys. Rev. D* ***103****, 103017* (2021) [2011.13833].

Michael A. Fedderke

mfedderke@jhu.edu
mfedderke.com

JOHNS HOPKINS UNIVERSITY

GW Detection Landscape



Strong science case for broad coverage!

Existing / proposed facilities provide good coverage.

But there is a gap…

The "μHz Gap"

Many interesting sources in the "gap":

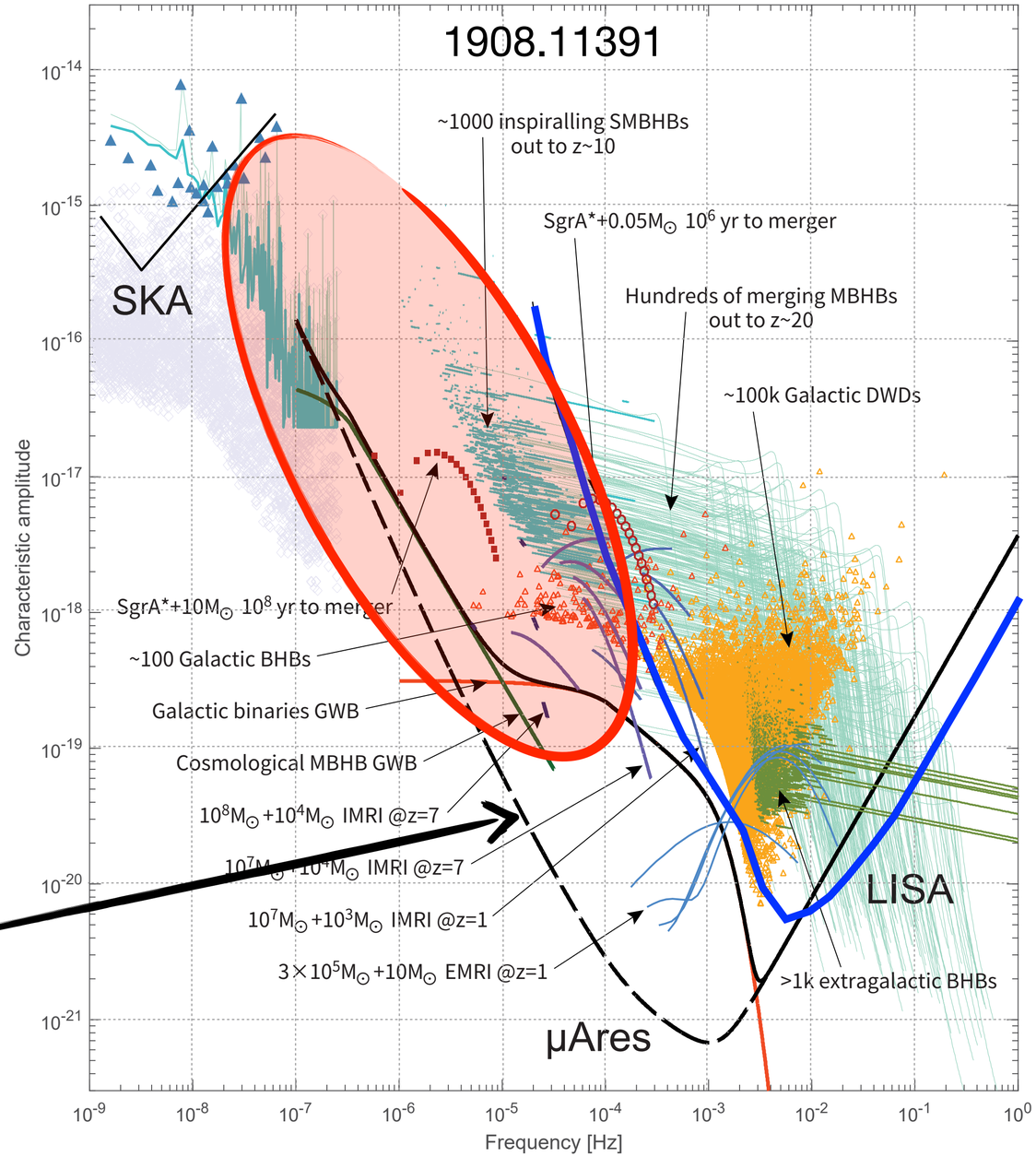
- Galactic binary black holes (BHBs)
- Cosmologically distant supermassive binary black holes (SMBHBs)
- $10M_\odot$ spiraling into SgrA*
- Intermediate mass ratio inspires (IMRIs)
- …

Some observational studies and approaches exist:

- μAres (LISA-style: bigger and better TM)
- Astrometric techniques

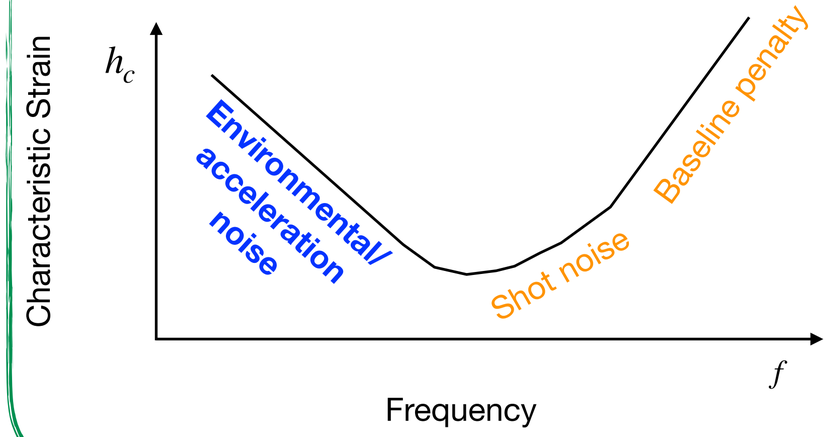
Strawman mission concept:
LISA-like, but with 3AU arms lengths, greatly improved low-frequency test masses

The μAres detection landscape

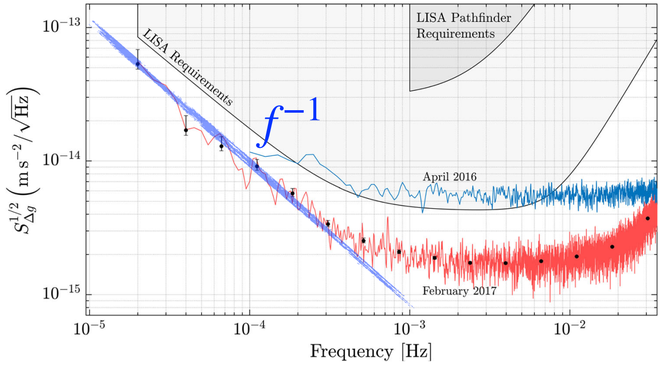


This band is challenging!

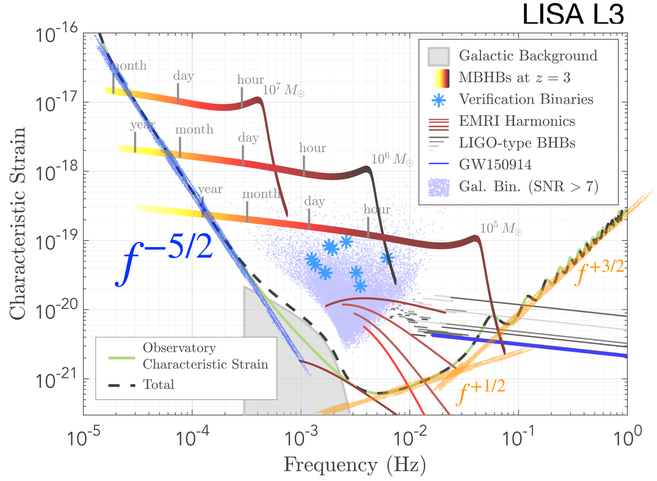
FROM ABOVE: LOCAL TM APPROACHES



LISA Pathfinder. Phys. Rev. Lett. **120**. 061101 (2018)

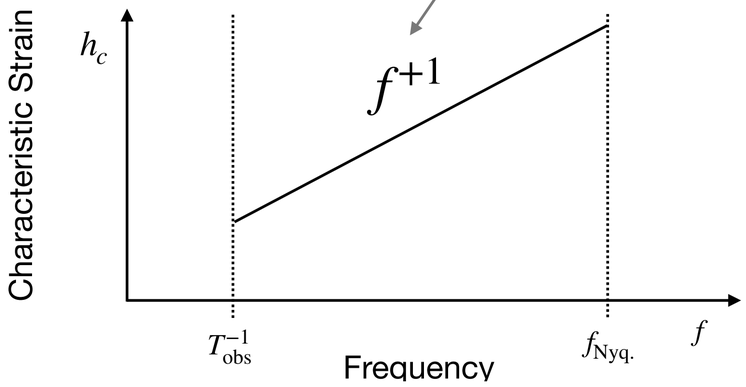


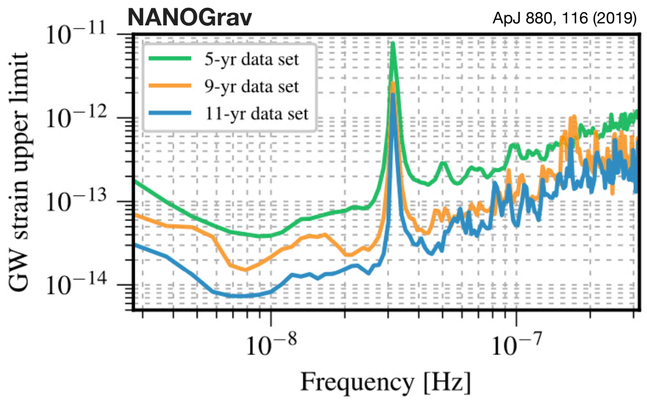
LISA L3



FROM BELOW: PTAs

Moore et al. *Class. Quantum Grav.* **32** 055004





Low-freqency "acceleration noise"	High-frequency "ranging noise"	
✗	✓	LISA-style
✓	✗	PTAs

Difficult to approach this band from either end with existing approaches

Michael A. Fedderke (JHU)

A Mission Concept

Can we use natural massive TM, but do it so we can build the ranging link?

Low-freqency “acceleration noise”	High-frequency “ranging noise”	
✗	✓	**LISA-style**
✓	✗	**PTAs**

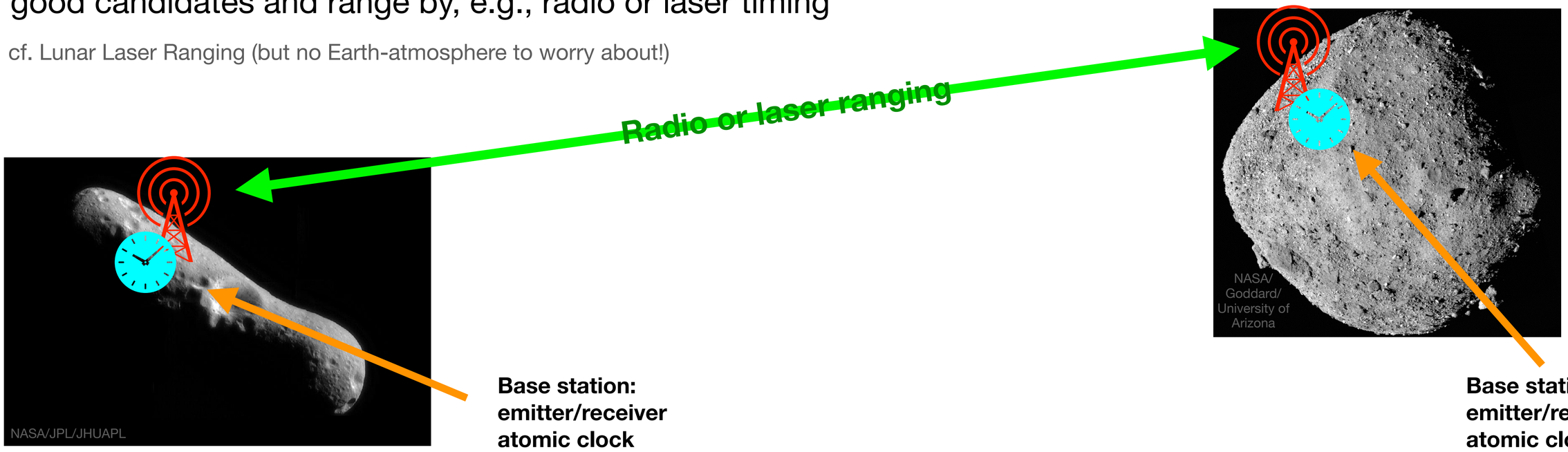
Rest of this talk:

evaluate asteroids* as the TM

See also talk by Yu-Dai Tsai earlier in the conference for a different idea using asteroids for fifth-force searches

Ranging: park base stations (clock + emitter/receiver) on good candidates and range by, e.g., radio or laser timing

cf. Lunar Laser Ranging (but no Earth-atmosphere to worry about!)



*One of the TMs could be a moon

Candidates and missions

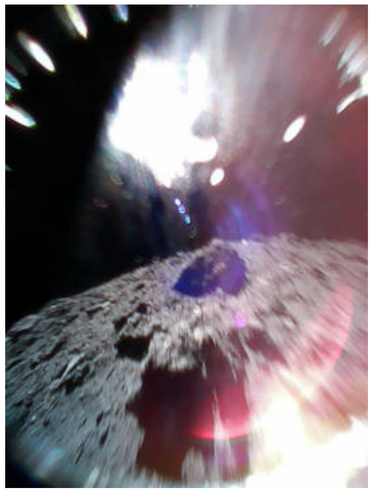
NASA JPL Small-Body Database

Asteroid	a [AU]	D [km]	$T_{\rm rot}$ [hrs]
433 Eros	1.46	16.8	5.3
1627 Ivar	1.86	9.1	4.8
2064 Thomsen	2.18	13.6	4.2
6618 Jimsimons	1.87	11.5	4.1

$$\sim 3 \times 10^{-5}\,\mathrm{Hz}$$

Mission	**Destination**	**Activity**	**Key Years**
NEAR-Shoemaker	433 Eros	orbiter / soft landing	2000/1
DAWN	Ceres, Vesta	orbiter	2010s
Hayabusa	25143 Itokawa	orbiter / landing / sample return	2005
Hayabusa2	162173 Ryugu	orbiter / hopping “rovers” / sample return	2018- (ongoing)
OSIRIS-REx	101955 Bennu	orbiter / sample return	2018-21
Rosetta	Comet 67P	orbiter / lander (Philae)	2014-16

Hayabusa2 @ Ryugu

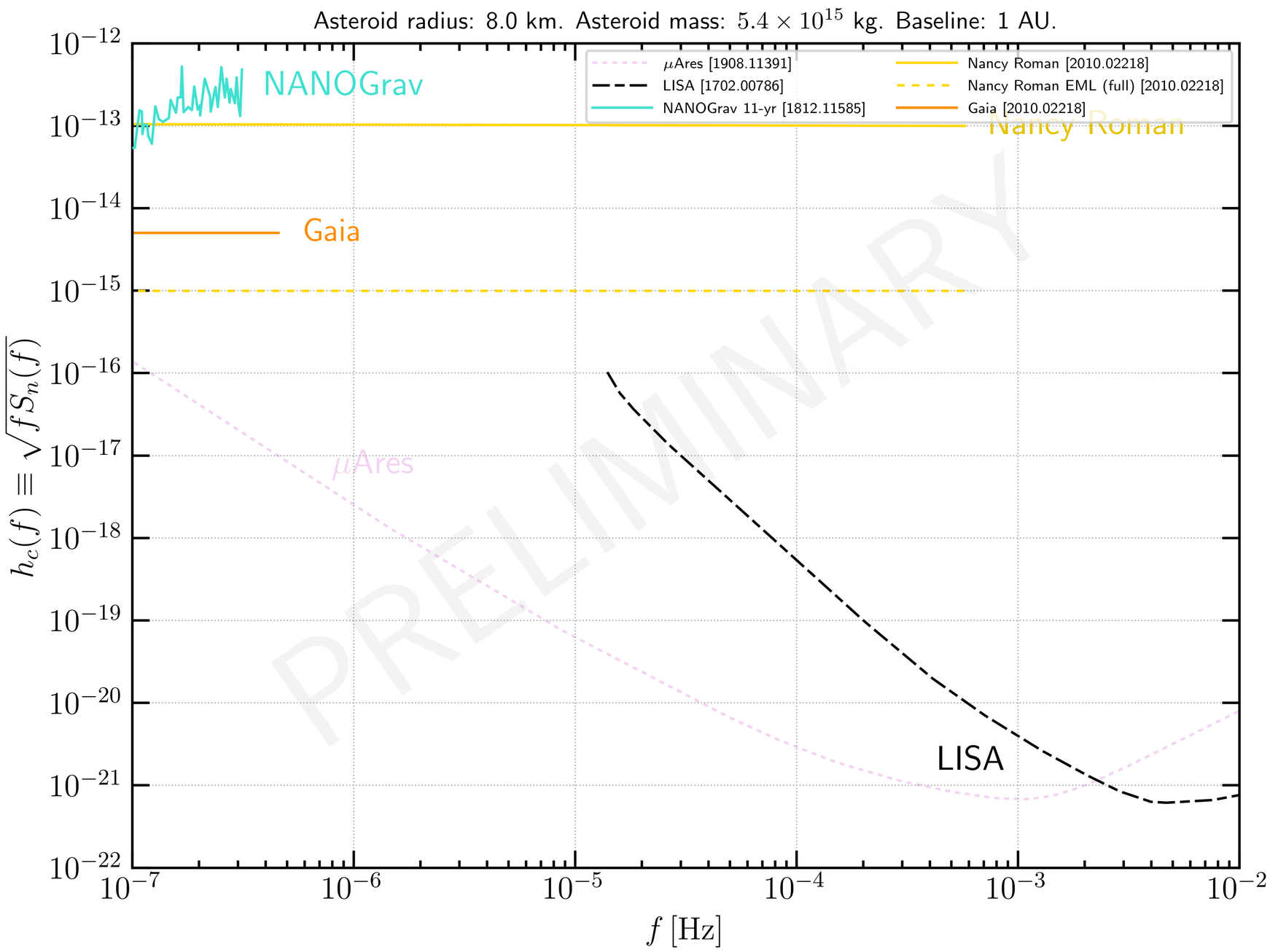


JAXA

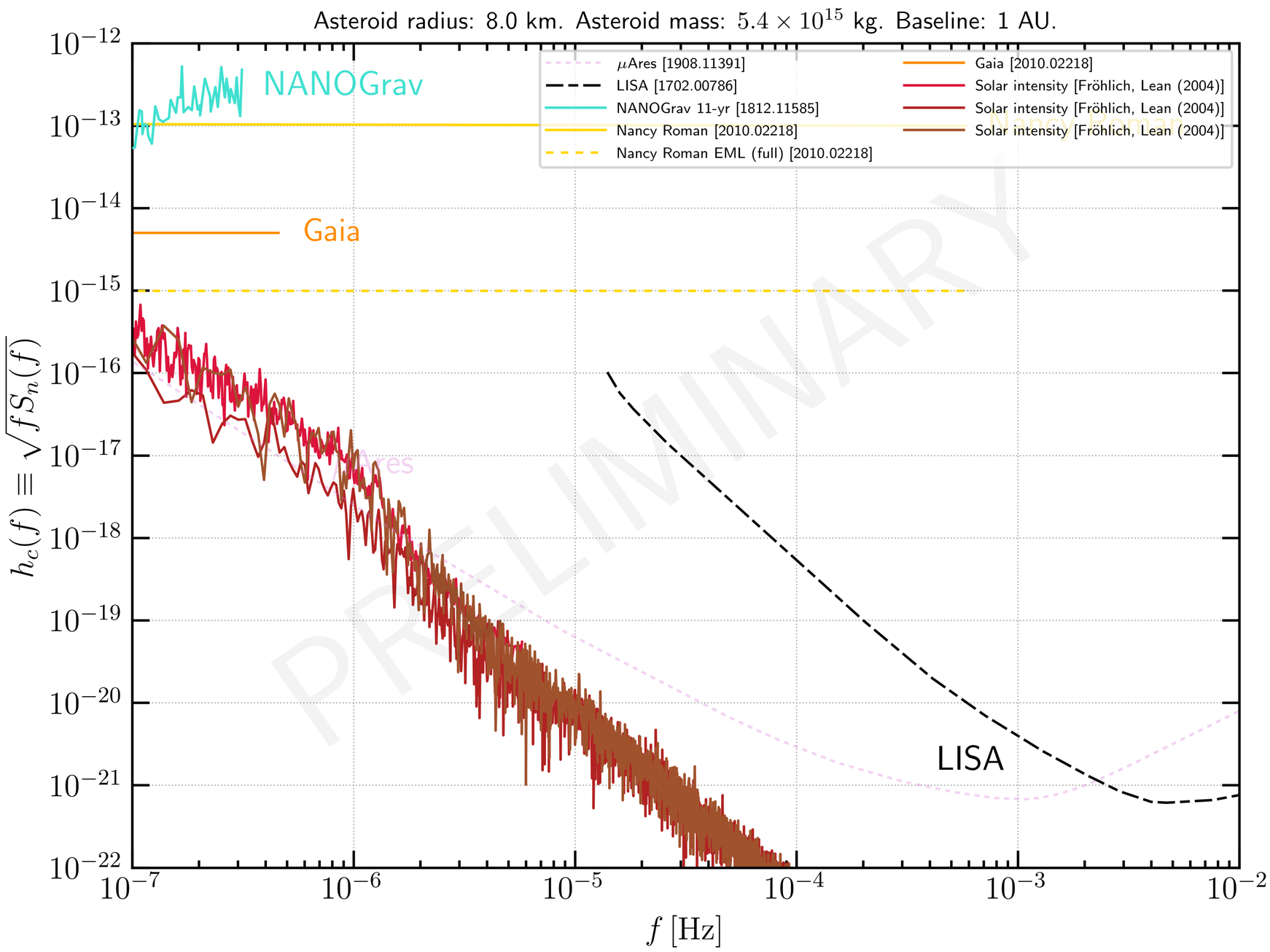
Note: Bennu is a “rubble pile”

OSIRIS-Rex @ Bennu

NASA/Goddard/University of Arizona



Existing or projected approaches in the μHz band



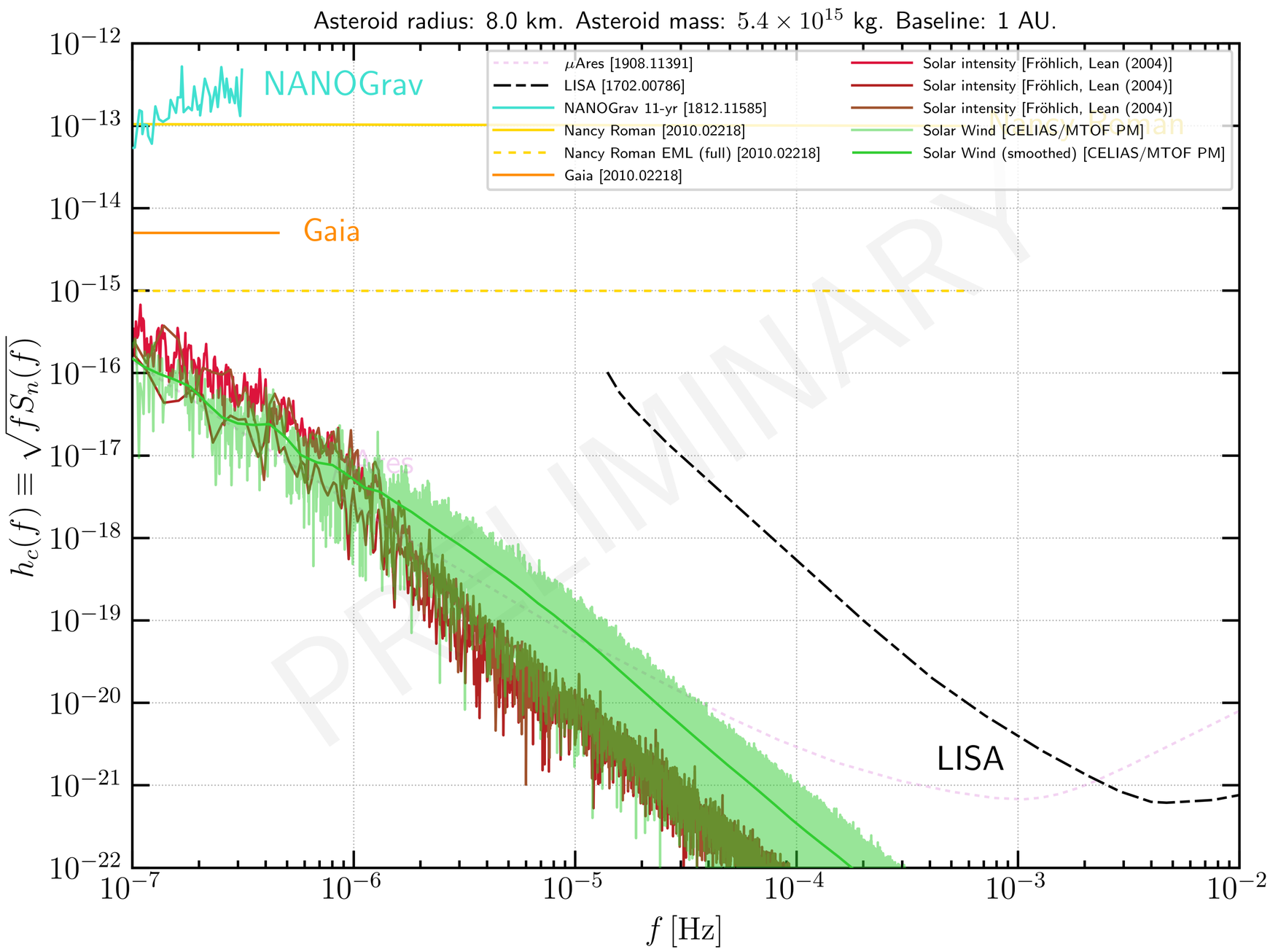
Solar intensity fluctuations

8km spherical asteroids at 1.5AU from the Sun, assuming fixed 1AU baseline (variation of out band)

$$\sqrt{S_a(f)} \sim \frac{\overline{P}_\odot}{c}\left(\frac{r_\oplus}{r}\right)^2 \frac{A_{\rm ast}}{M_{\rm ast}}\sqrt{S_{\hat{P}}(f)}$$

$$h_c \sim (2\pi f)^{-2} L^{-1}\sqrt{f S_a(f)}$$

MEASURED FRACTIONAL SOLAR PSD
Fröhlich and Lean [Astron. Astrophys. Rev. 12 (2004) 273—320]



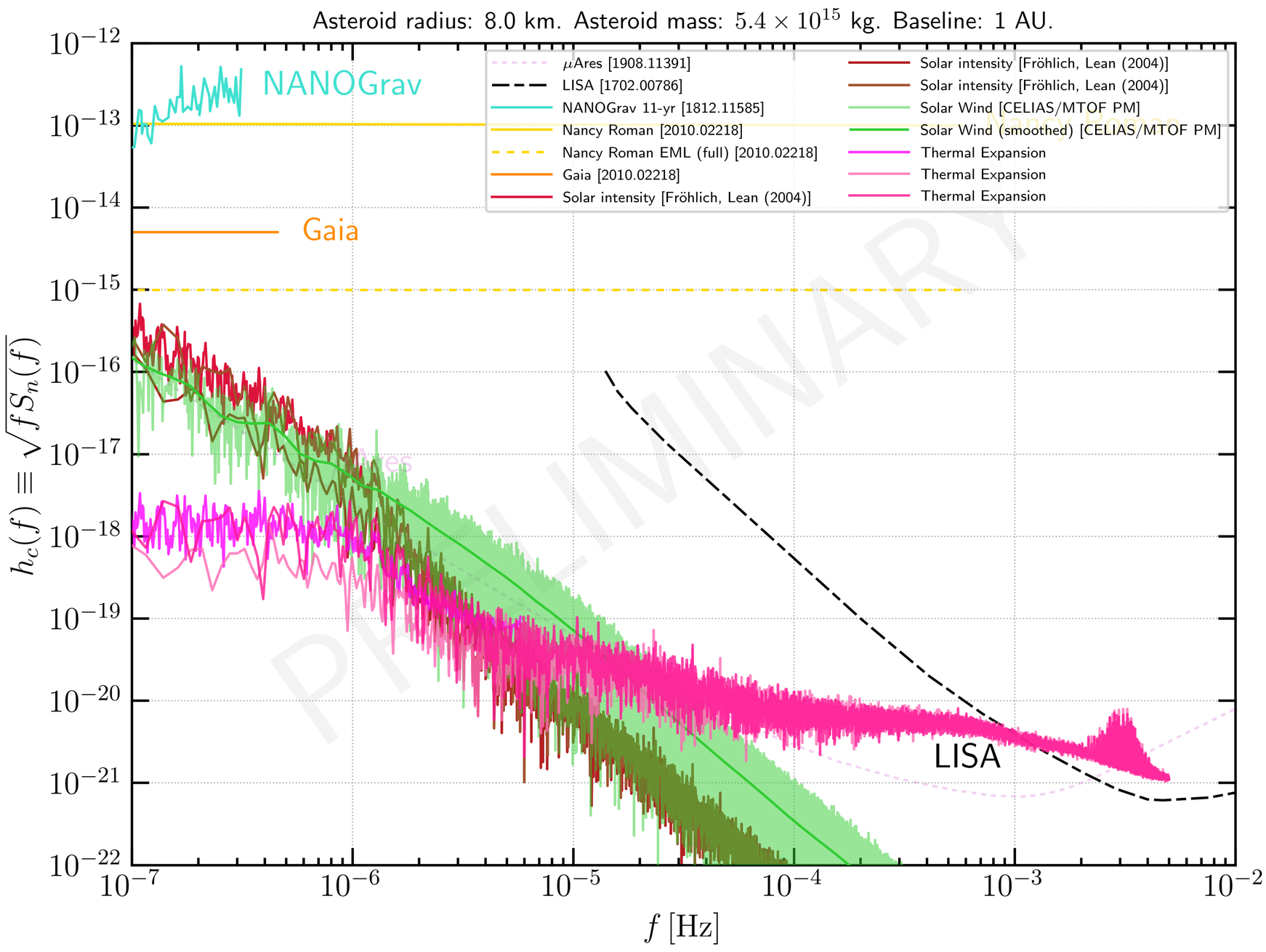
Solar wind fluctuations

Similar estimate to the intensity fluctuations:

$$\sqrt{S_a(f)} \sim m_p \left(\frac{r_\oplus}{r}\right)^2 \frac{A_{\rm ast}}{M_{\rm ast}} \sqrt{S_\Omega(f)}$$

$$\Omega = n_p v_p^2$$

Proton flux and speed monitored by the CELIAS/MTOF proton monitor on SOHO



Thermal cycling

Gigantic noise at rotation frequency, but out of band

Relevant estimate is from in-band surface temperature fluctuations arising from solar intensity fluctuation

Expansion from heating upper

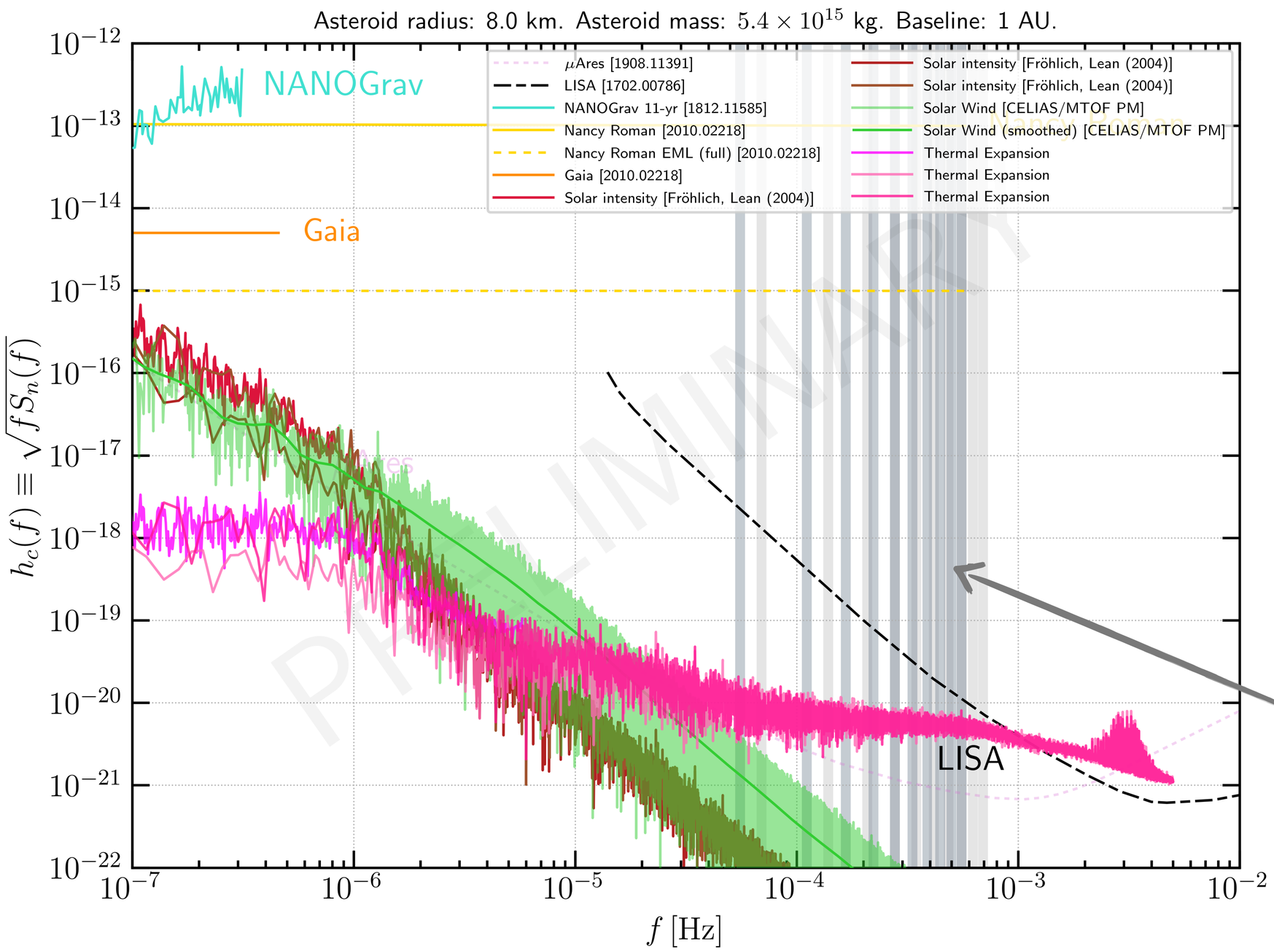
$$d_{\text{th.}} \sim 1\,\text{m} \times \sqrt{\mu\text{Hz}/f}$$

of the asteroid

(rock estimate - conservative, since regolith is a blanket)

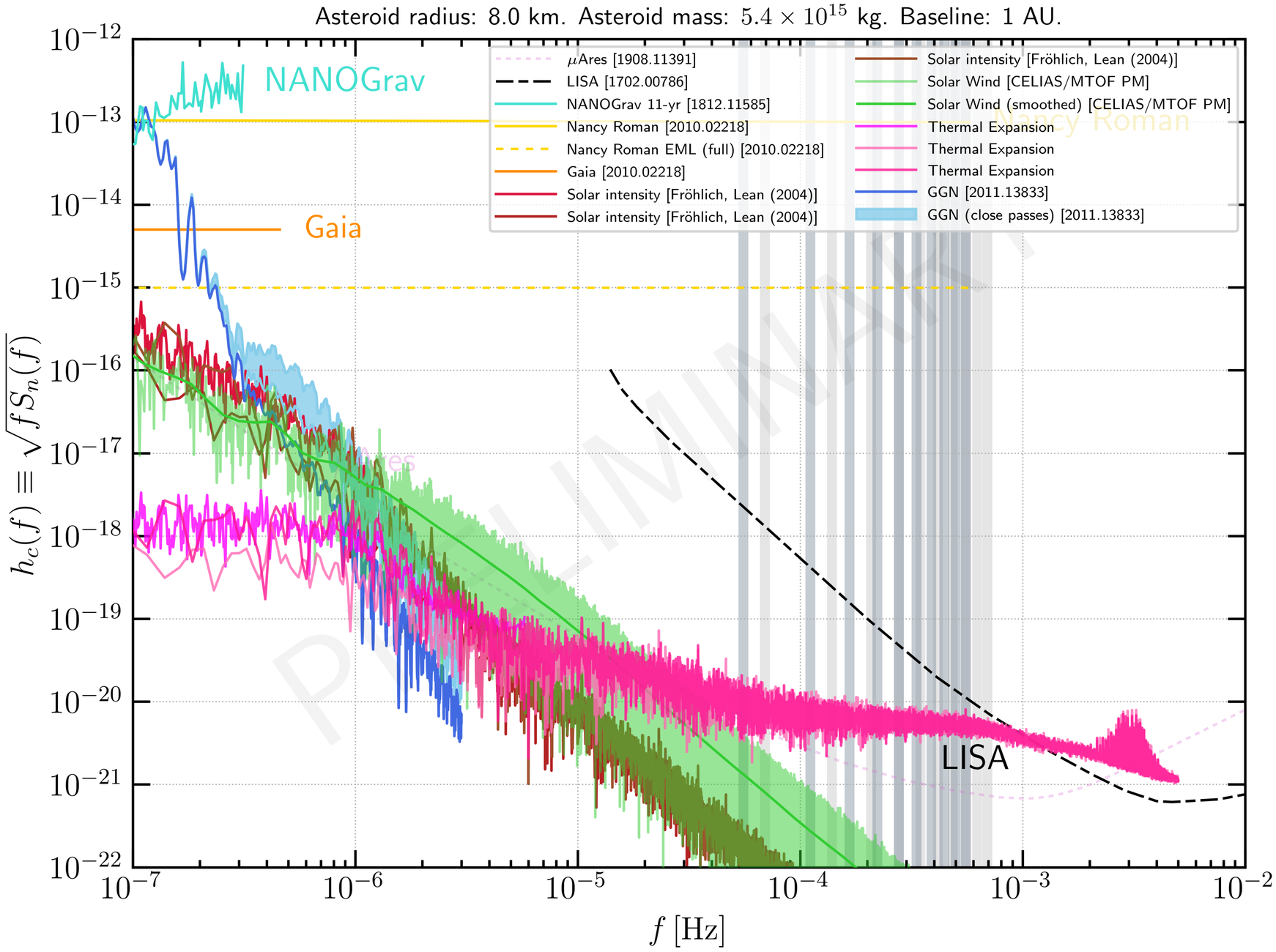
$$\Delta x \sim \frac{1}{3} d_{\text{th.}} k_{\text{th.}} \Delta T$$

$$\Delta T \sim \frac{1}{4} \overline{T} \sqrt{f S_{\hat{P}}(f)}$$



Severe noise at rotational period(s)

4/5 hrs & harmonics



Asteroid GGN

Sum over $\sim 10^6$ other asteroids (in Main Belt, and some close-passers) give a noise for ***all*** local-TM-based proposals operating in the inner Solar System.

M.A.F., P.W. Graham, and S. Rajendran. *Phys. Rev. D* ***103***, *103017* (2021) [2011.13833].

Note: also get cut off severely by uncontrolled relative motion of asteroids around orbital frequencies.

...other acceleration noise sources estimated, sub-dominant: charging, magnetic forces and torques, collisions, tidal deformation, etc.

Seismic noise

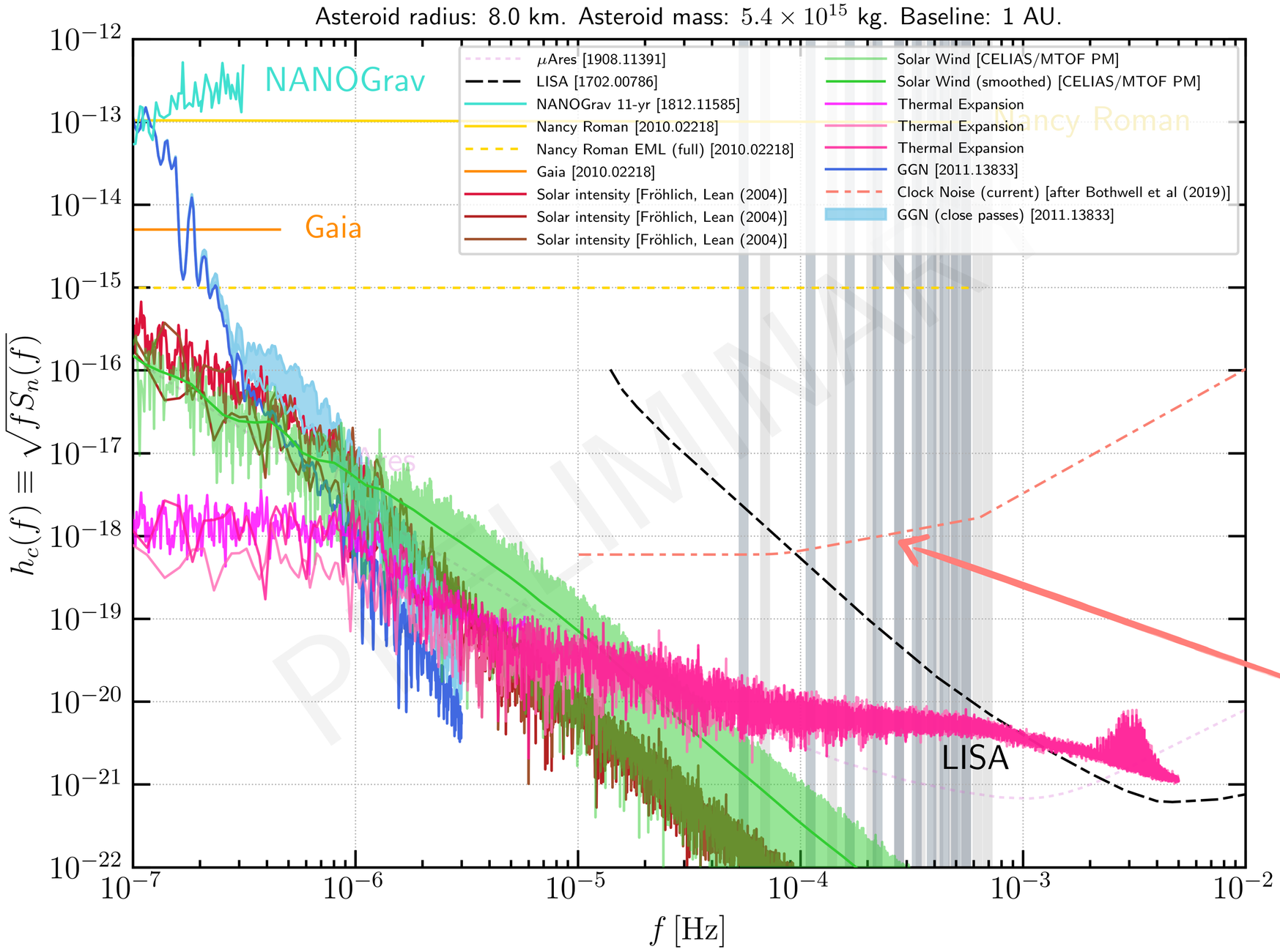
- Asteroids are ancient, dead rock: no tectonics, no residual heat.

- Pick asteroids that are ~ solid
  - There simply aren't resonant frequencies to excite in our band!
    - 433 Eros: lowest normal-mode frequency is ~10 mHz [Walker, Sagebiel, Huebner. Adv. Space Res. 37 (2006) 142—152]

- Seismic measurements on the Moon and Mars typically have amplitudes of ~few nm (around ~Hz): $h \sim 10^{-20}$ for AU baselines

- **<u>Motivates seismic experiments on future asteroid missions</u>**
  (already motivated by internal structure studies [e.g., APEX mission concept])

Clock Noise



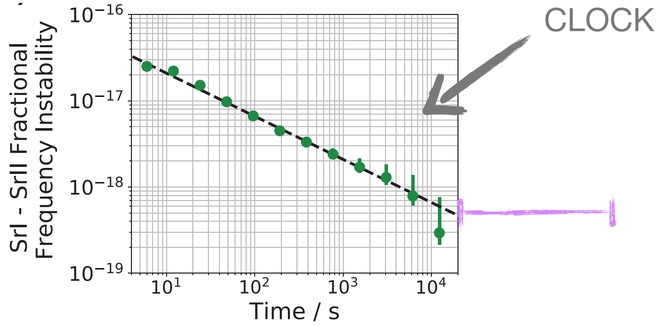
Ranging is by, e.g., return-trip pulse timing.

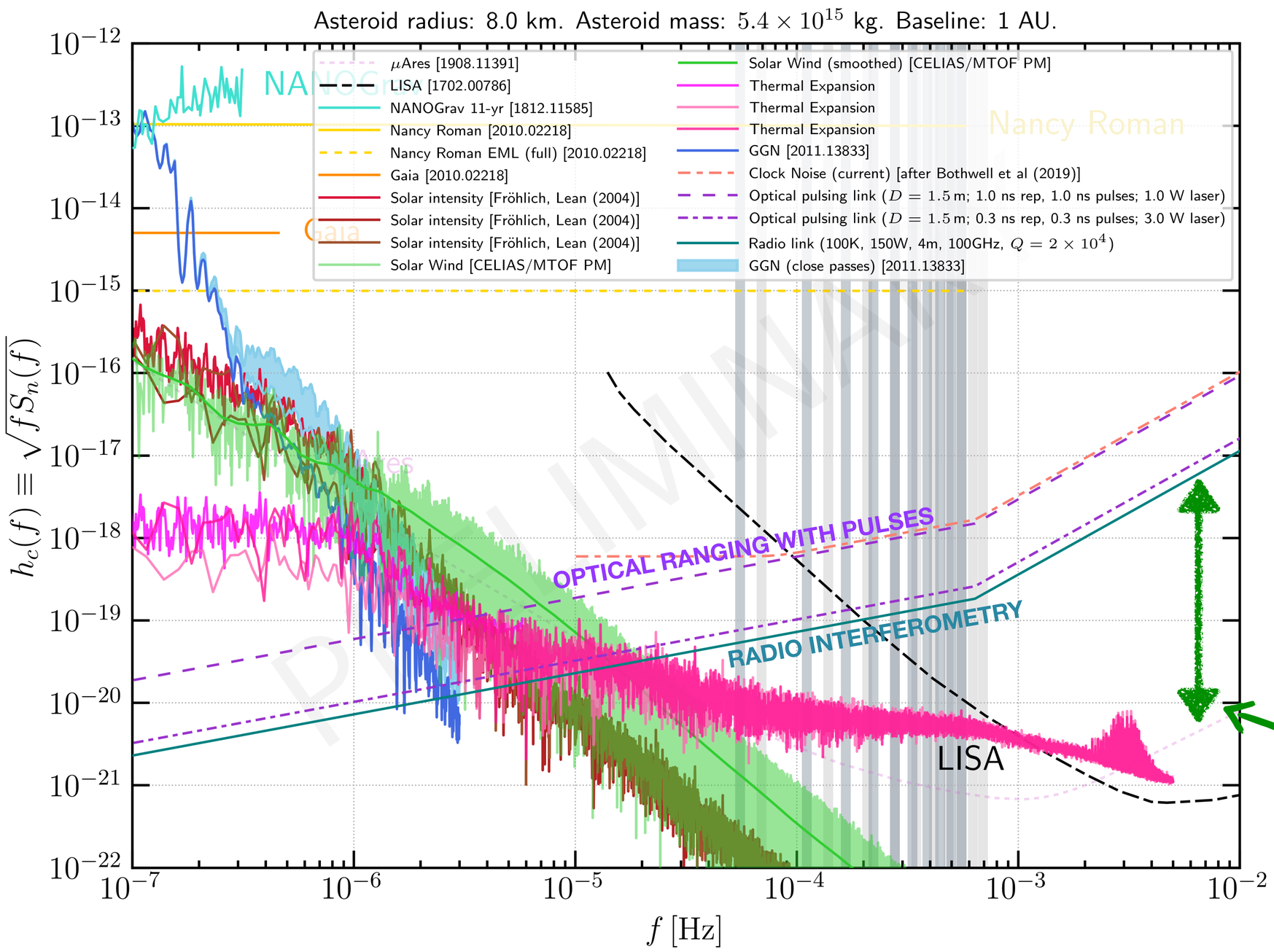
Existing ground-based clocks are already sufficient for excellent reach.

Clock accuracy improvement extremely rapid. Probably not a limit.

<u>Further motivates space-qualification of atomic clocks.</u>

Translated/extrapolated from Bothwell et al. Metrologia 56 (2019) 065004.





Link Noise

Distance measurement by round-trip timing / “radar ranging”

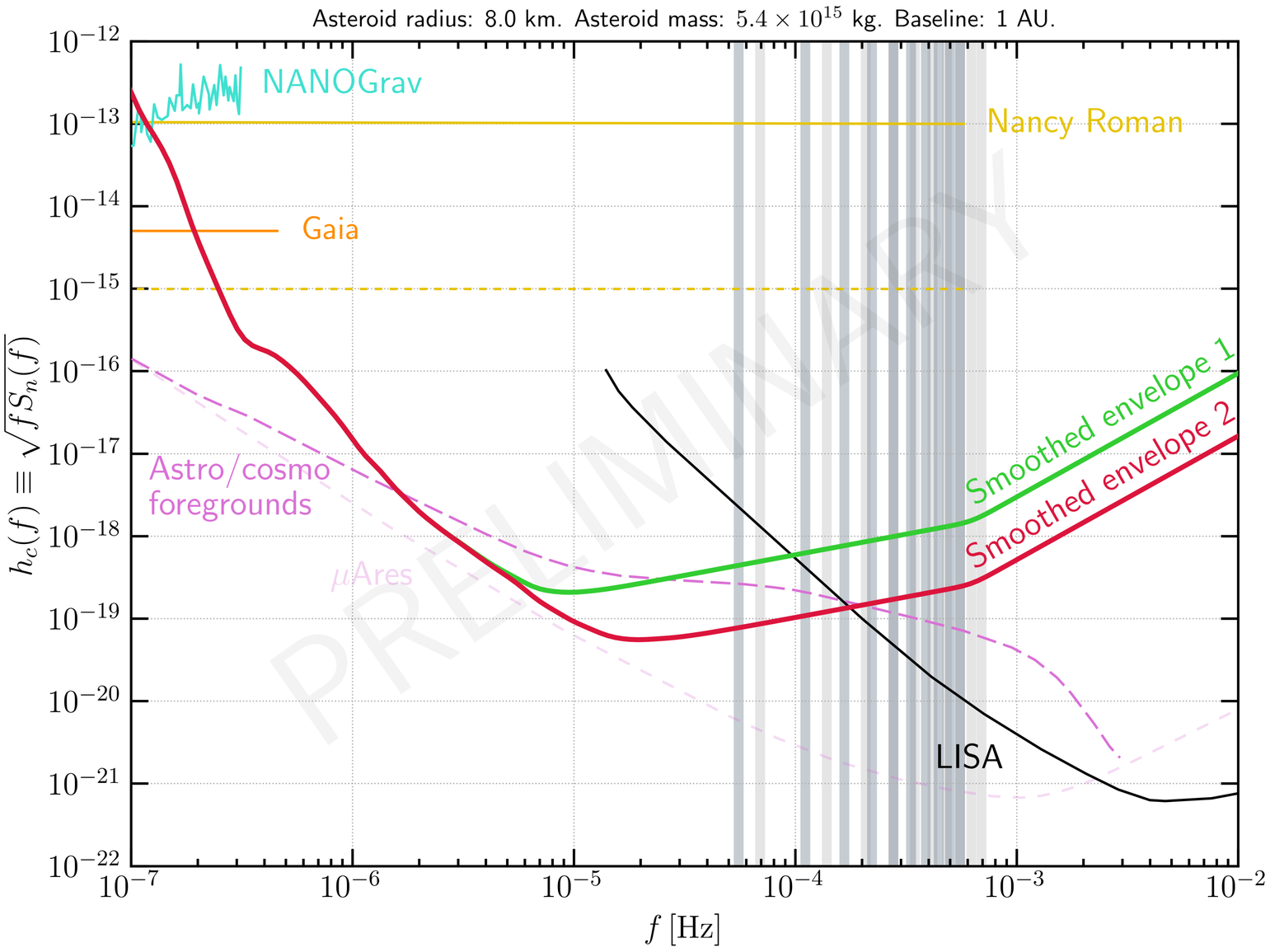
Shot noise of laser pulsing link OR thermal noise from radio interferometric link.

Exemplar curves shown.

Asteroids are (obviously) **not** in formation flight. LISA-class heterodyne optical interferometry links would be **hard**, but **can significantly relax optical system requirements**!

*NOTE: WE HAVE NOT ACCESSED THE ENGINEERING CHALLENGES OF BUILDING THESE LINKS!

Projected Sensitivity Curves



Asteroids are excellent test masses for a GW detector in the μHz band

Laser/radio ranging between on-asteroid base stations equipped with transmit/receive capability and atomic clocks gets excellent sensitivity

Further strongly motivates:

- in-situ seismic / plastic deformation monitoring of asteroids in upcoming missions
- space-qualifying atomic clocks

Thanks!