Bridging the μHz gap with asteroids

Gravitational Wave Probes of Physics Beyond Standard Model

Remote presentation

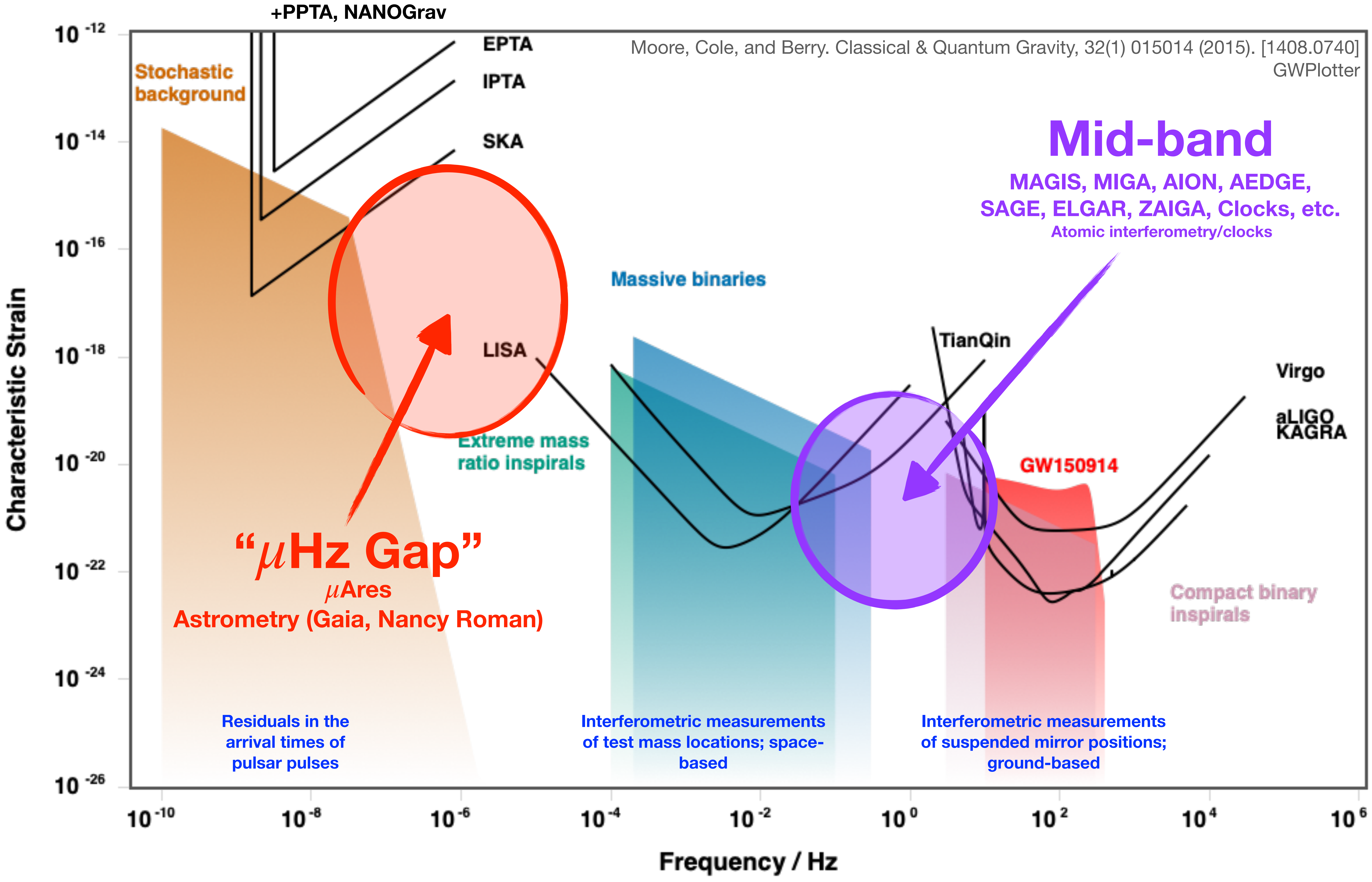
July 15, 2021

M.F., P.W. Graham, and S. Rajendran. *Forthcoming* (2021). [210x.yyyyy].
M.F., P.W. Graham, and S. Rajendran. *Phys. Rev. D* ***103**, 103017* (2021) [2011.13833].

Michael A. Fedderke
mfedderke@jhu.edu

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)
- $10M_\odot$ spiralling into SgrA*
- Intermediate mass ratio inspires (IMRIs)
- …

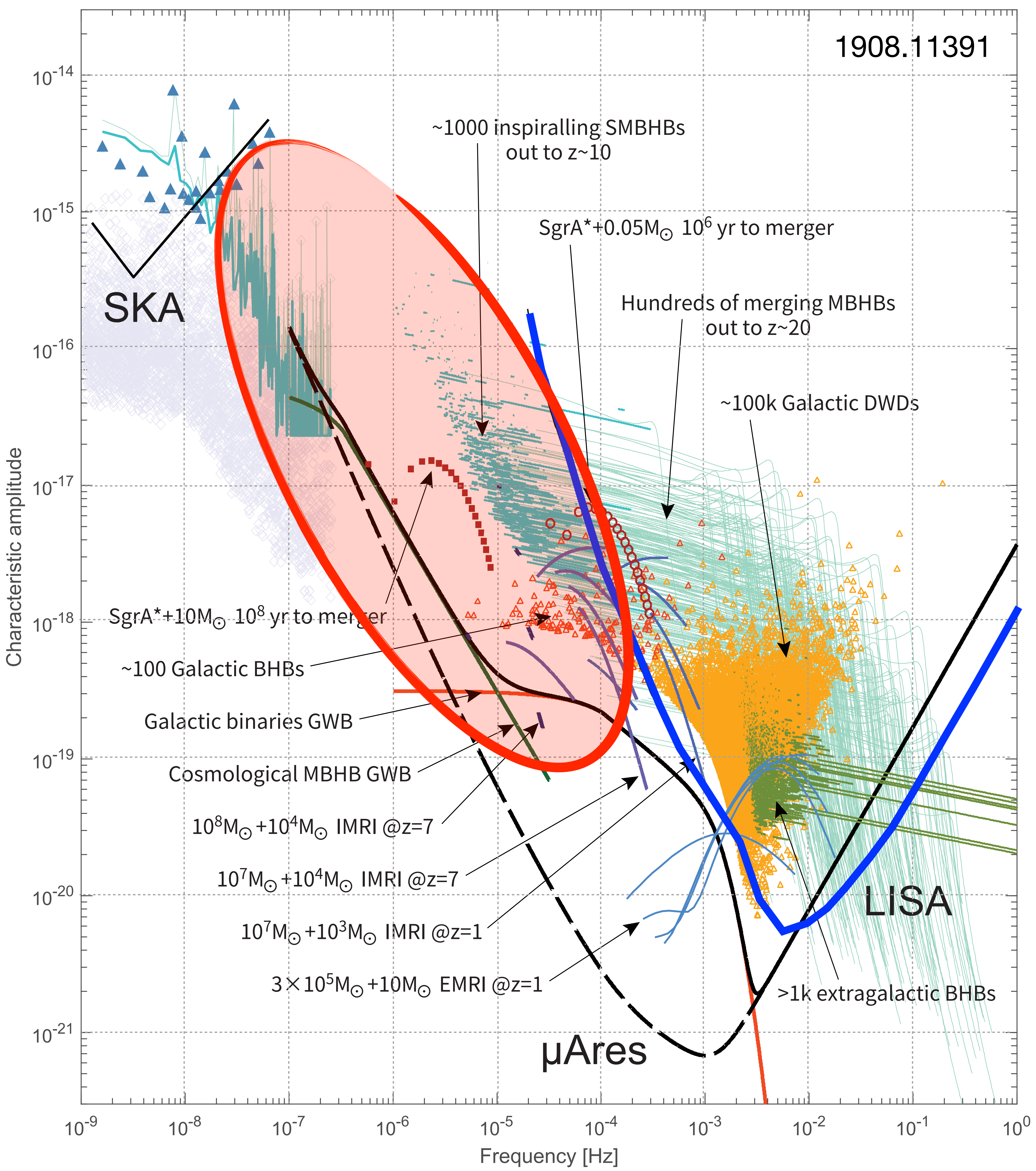
Some observational studies and approaches exist:

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

Singularly hard to build detectors in this band!

Why?

The μAres detection landscape



Michael A. Fedderke (JHU)

Local-TM—based GW Detection 101

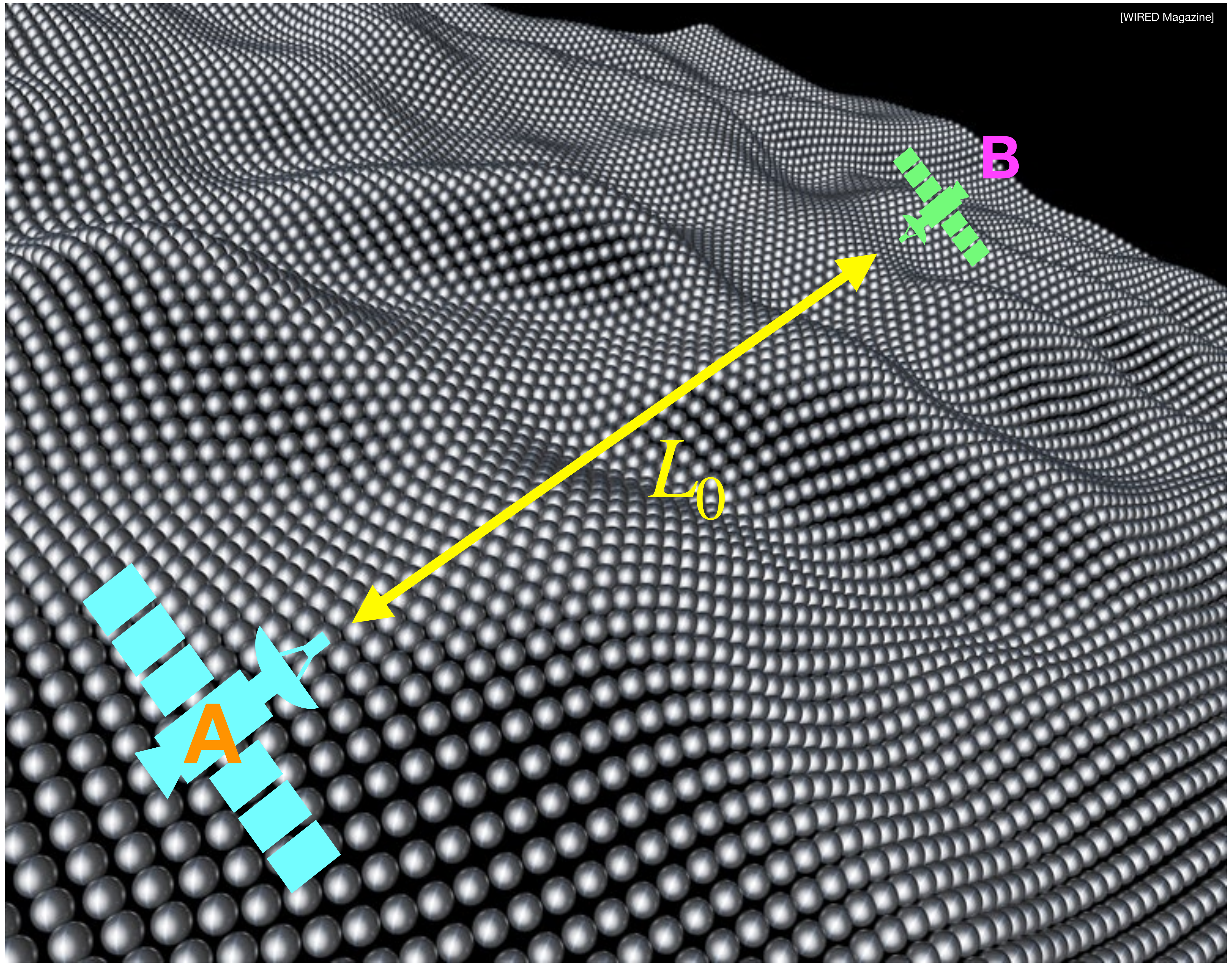
- Measure light travel time (= proper distance) between test masses (TM)
- Emitter (A) sends pulse at $t_A = t_0$;
  receiver (B) gets pulse at $t_B = t_0 + \Delta t$:

$$\Delta t = L_0 \left(1 - \frac{h_0}{2} \operatorname{sinc}(\omega_{gw} L_0/2) \cos[\omega_{gw}(t_0 + L_0/2)] \right) + \mathcal{O}(h_0^2)$$

$$\longrightarrow L_0 \left(1 - \frac{h_0}{2} \cos[\omega_{gw} t_0] \right) + \mathcal{O}(h_0^2) \qquad [\omega_{gw} L_0 \ll 1]$$

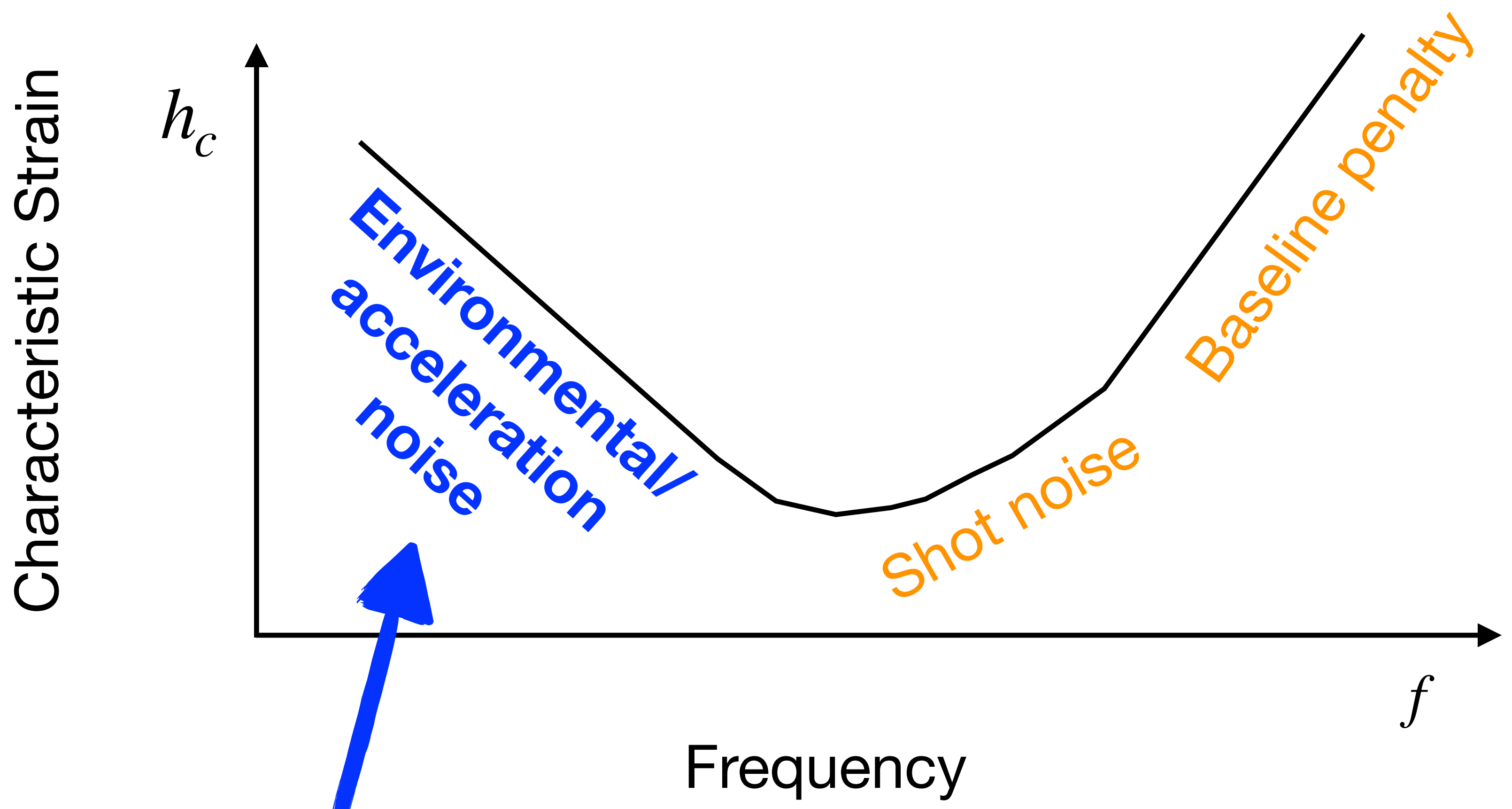
- Effective baseline-projected Newtonian acceleration a_L:

$$a \sim \frac{1}{2} h_0 \omega_{\mathrm{GW}}^2 L_0 \cos[\omega_{\mathrm{GW}} t_0]$$



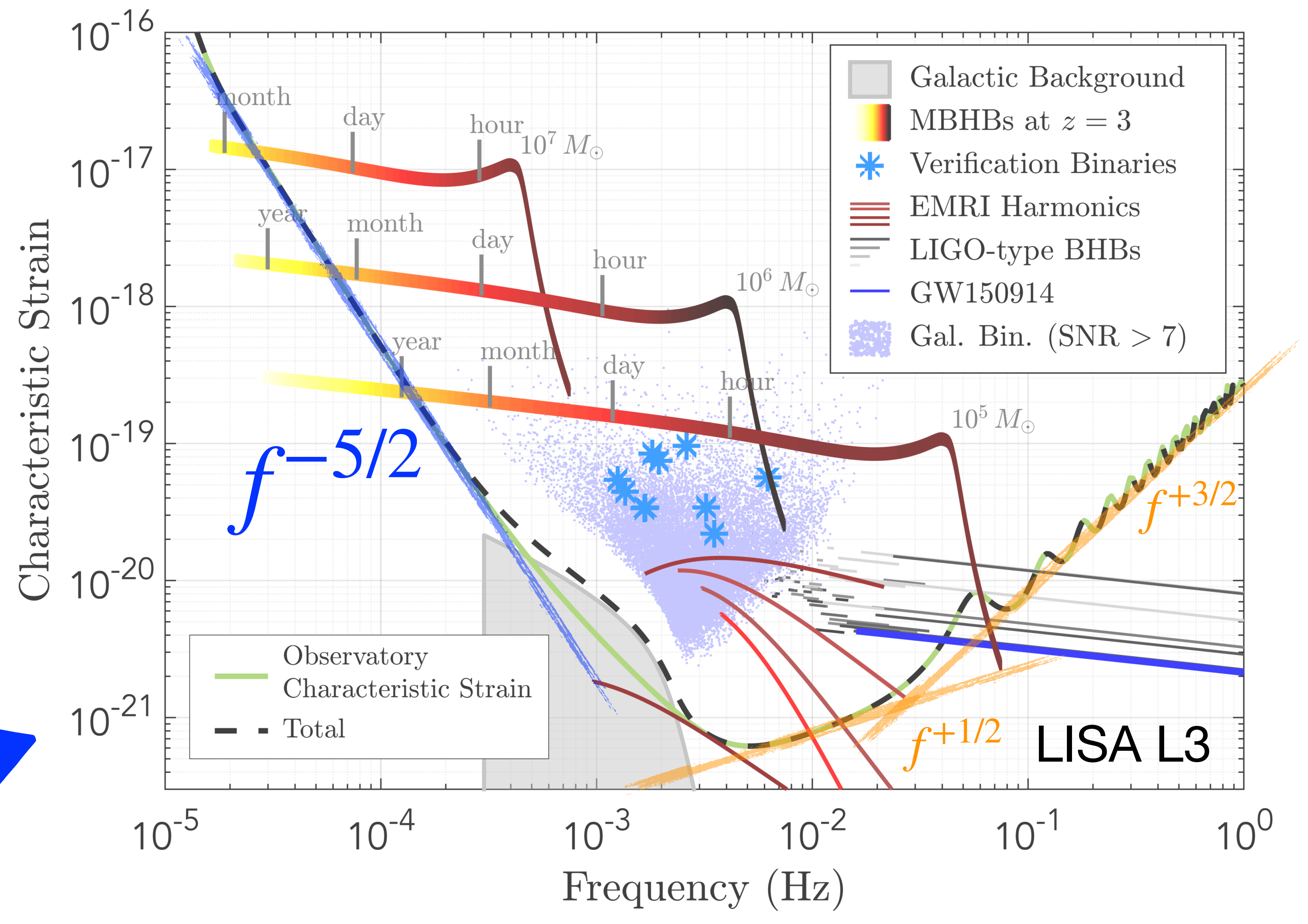
Michael A. Fedderke (JHU)

Sensitivity and Dominant Noise (local-TM)



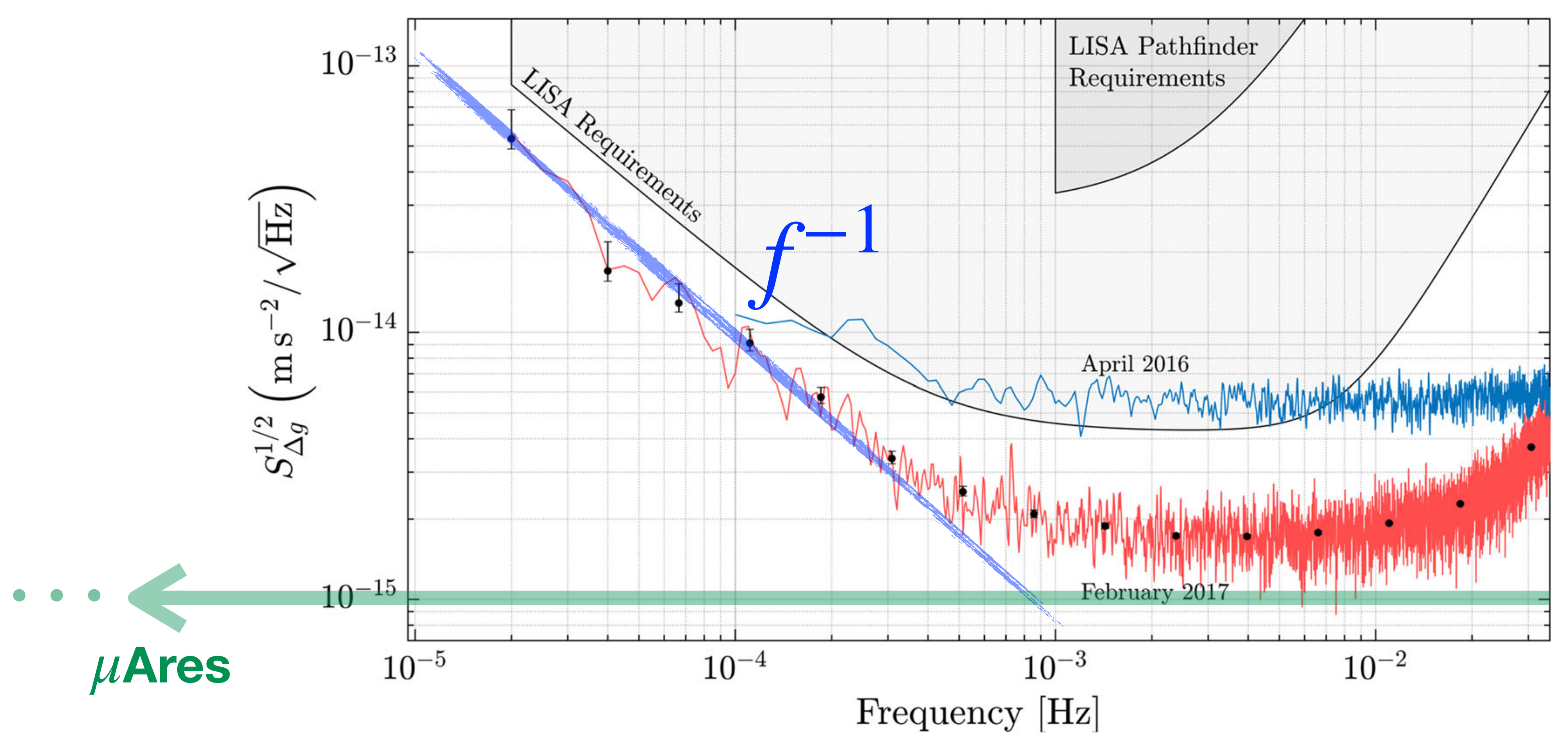
- Residual gas
- Charging
- TM actuator noise
- Laser intensity noise
- etc.

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



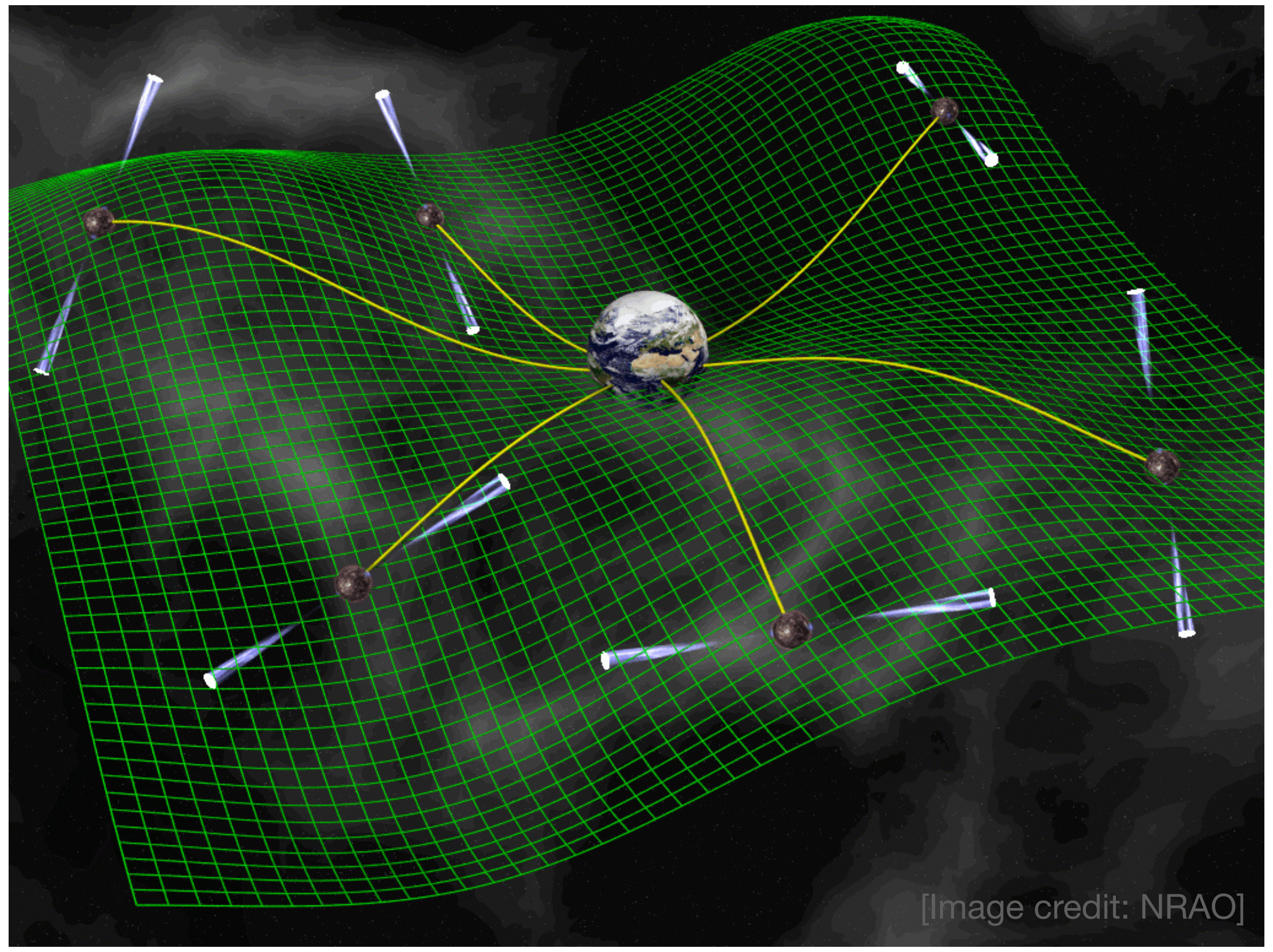
- $h_c \propto L^{-1} f^{-2} \sqrt{f S_a}$ $\qquad \sqrt{S_a} \propto f^{-1} \Rightarrow h_c \propto f^{-5/2}$ (LISA)
- How to improve?
  - Longer arms: $h_c \propto L^{-1}$ (μAres ~ 2AU ~ 300Gm vs LISA ~ 3Gm)
  - Better isolation engineering / reduce acc'n noise (μAres assumes $\sqrt{S_a} \propto f^0$)
  - Use a much heavier TM? (LISA: 2kg Au/Pt cube)

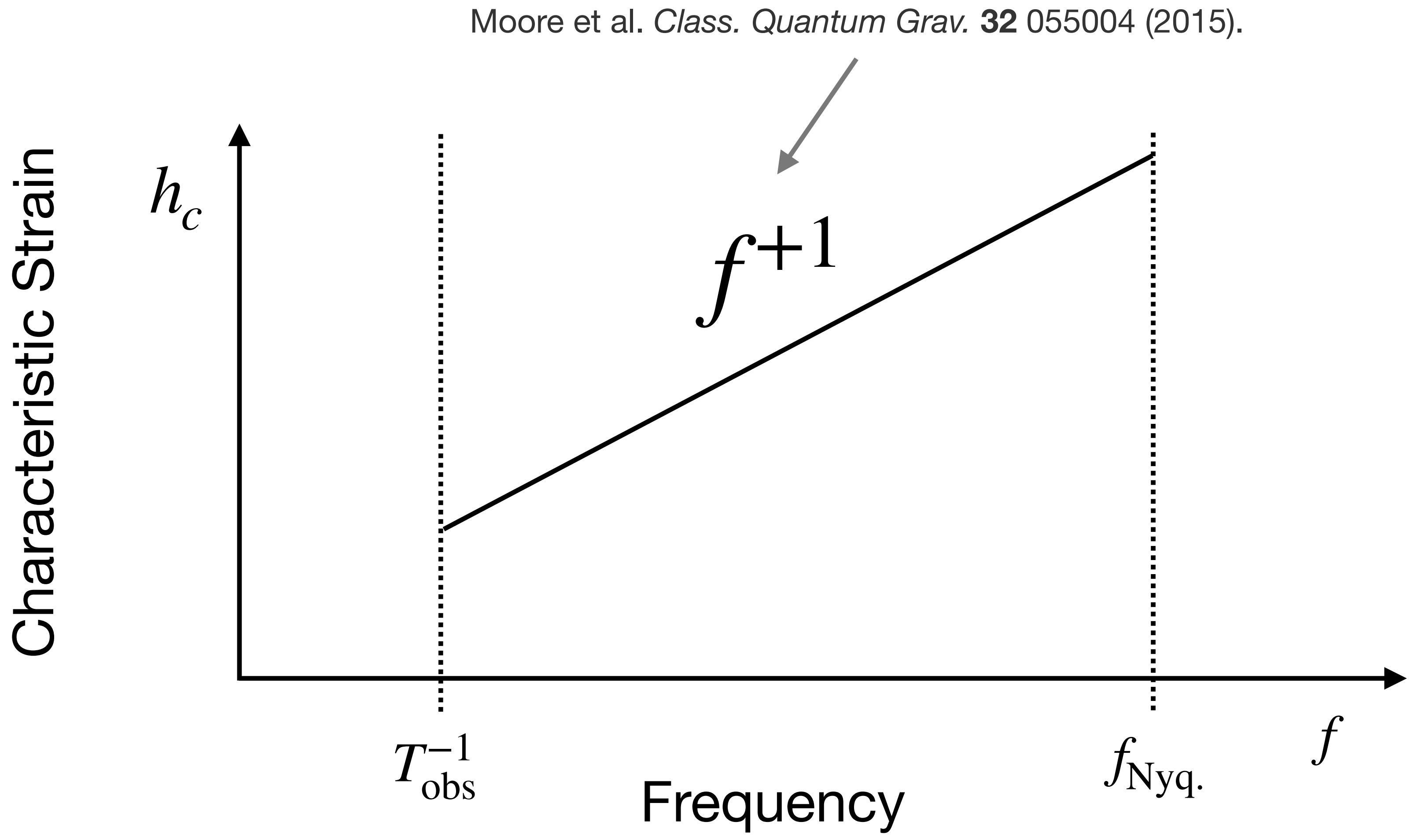
LISA Pathfinder. Phys. Rev. Lett. **120**, 061101 (2018)

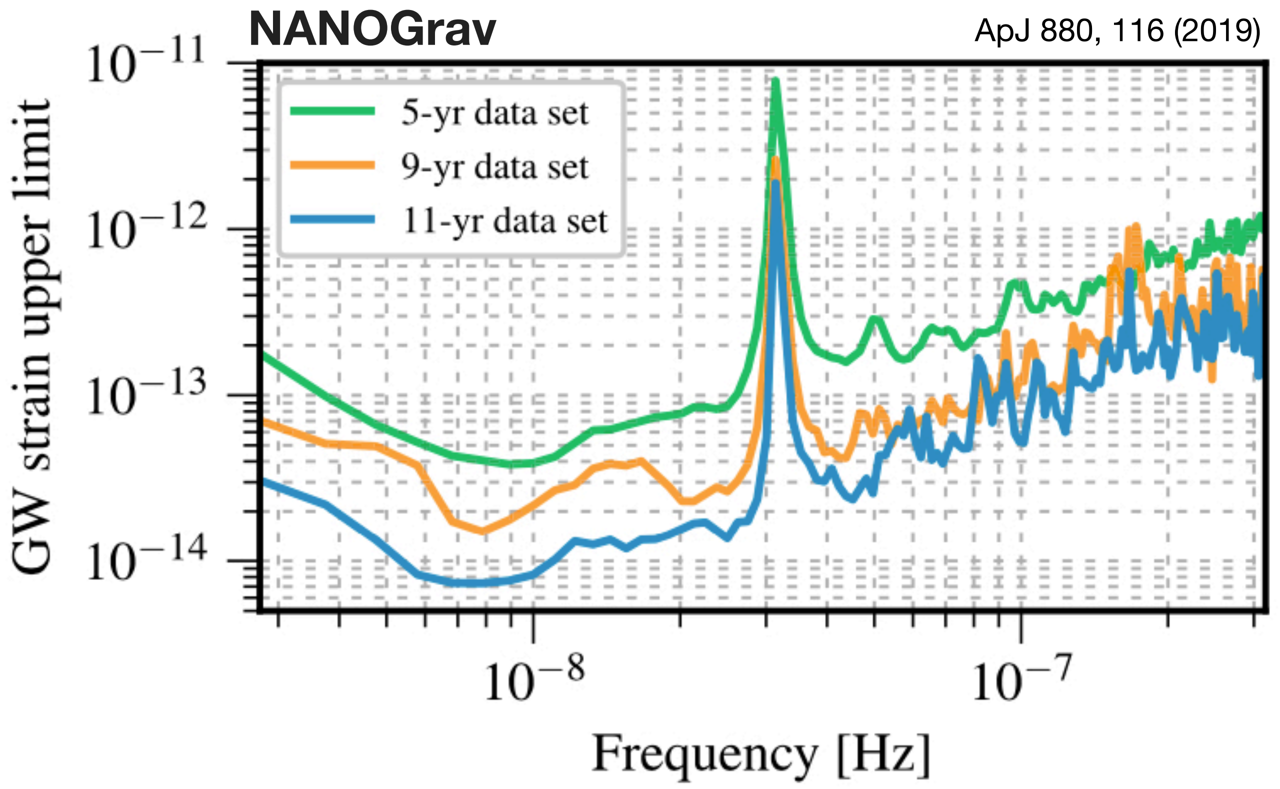


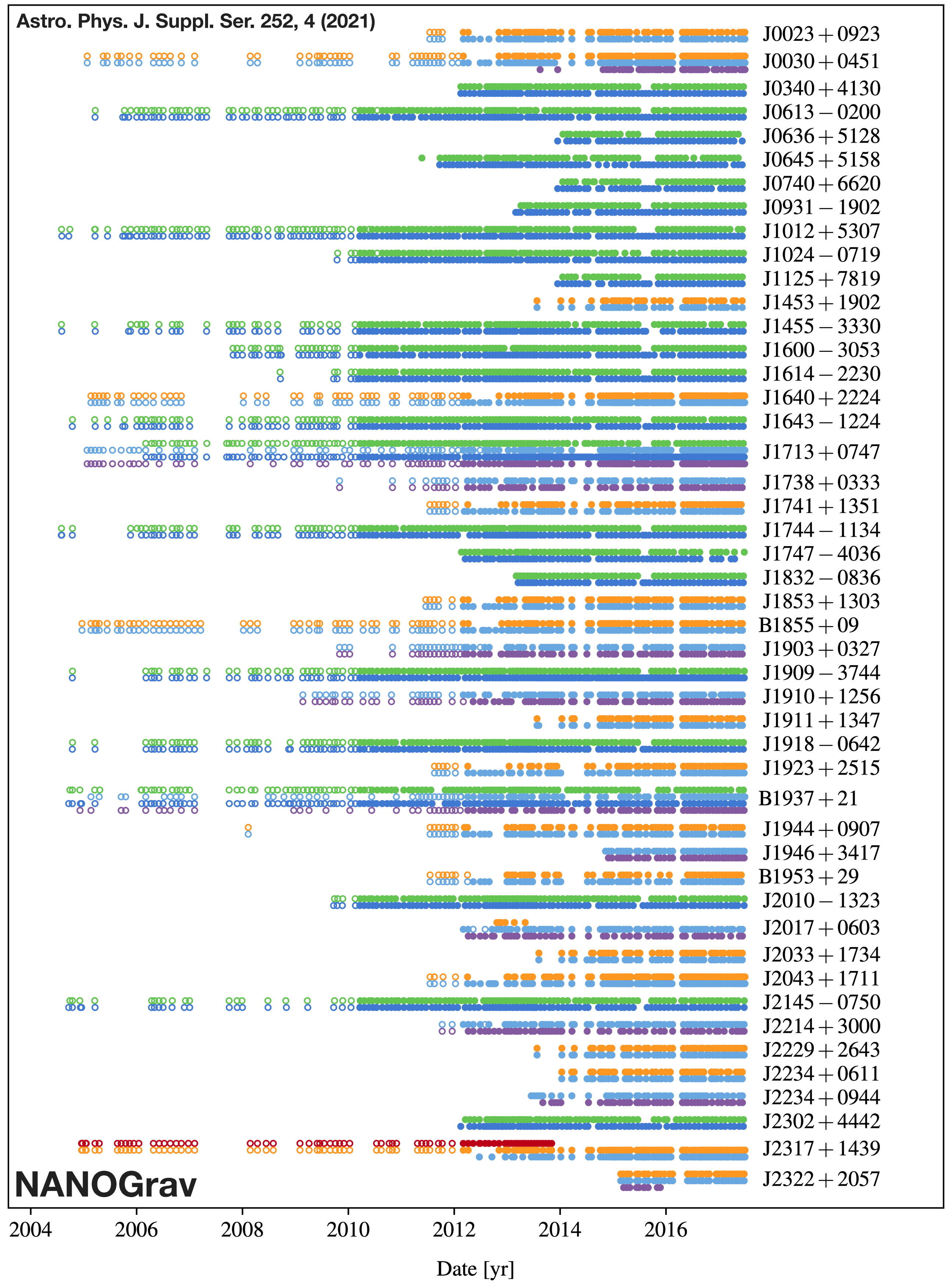
Michael A. Fedderke (JHU)

PTAs









- Pulsars are excellent TM (very massive) and clocks (excellent rotational stability)
- Measure pulse arrival times for many pulsars for > decade
- Timing residuals shift if GW passes (through Earth; pulsar terms average out)
- Lose sensitivity in the μHz band: limited timing residuals (~ 10ns), and observation cadence

A Mission Concept

μHz band difficult with existing approaches

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

A Mission Concept

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

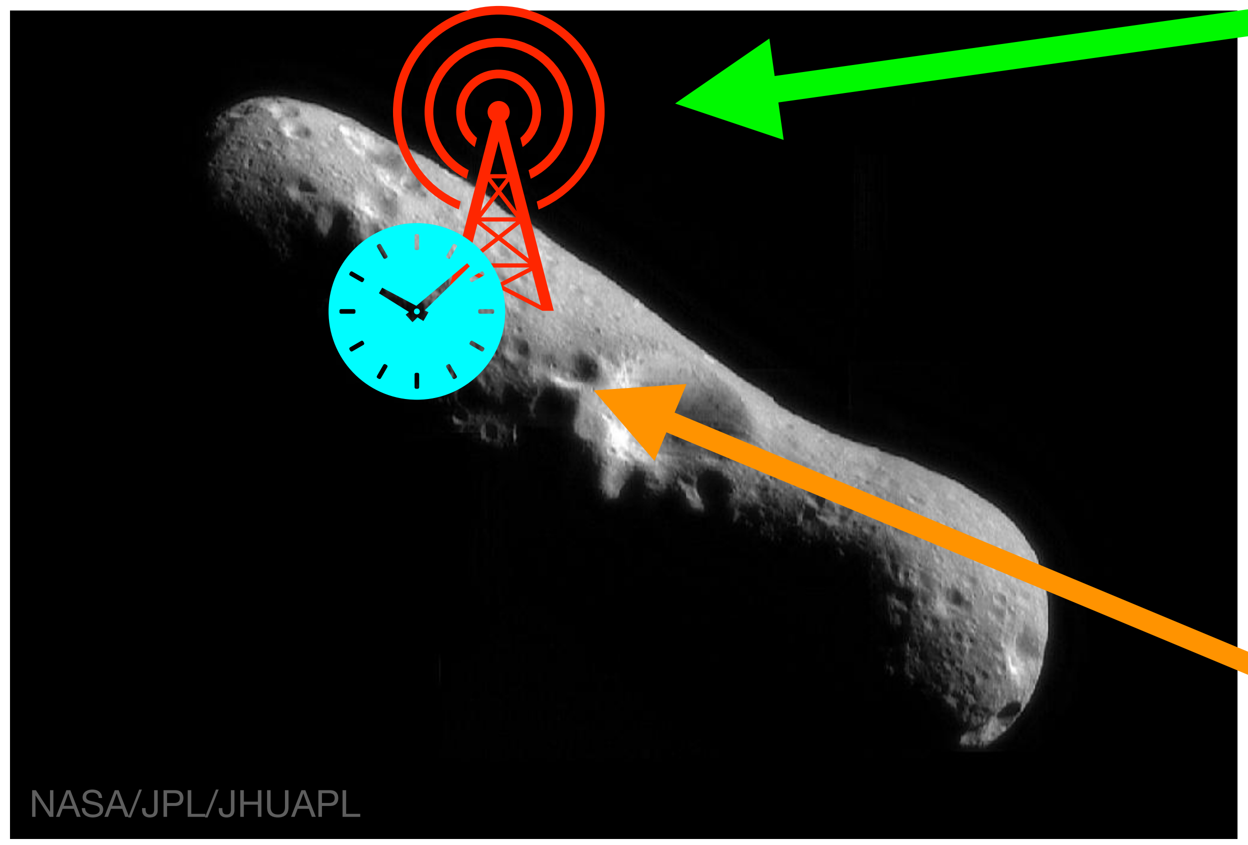
Can we use natural massive TM, but do it so we can build the ranging link?

Rest of this talk: evaluate asteroids as the TM

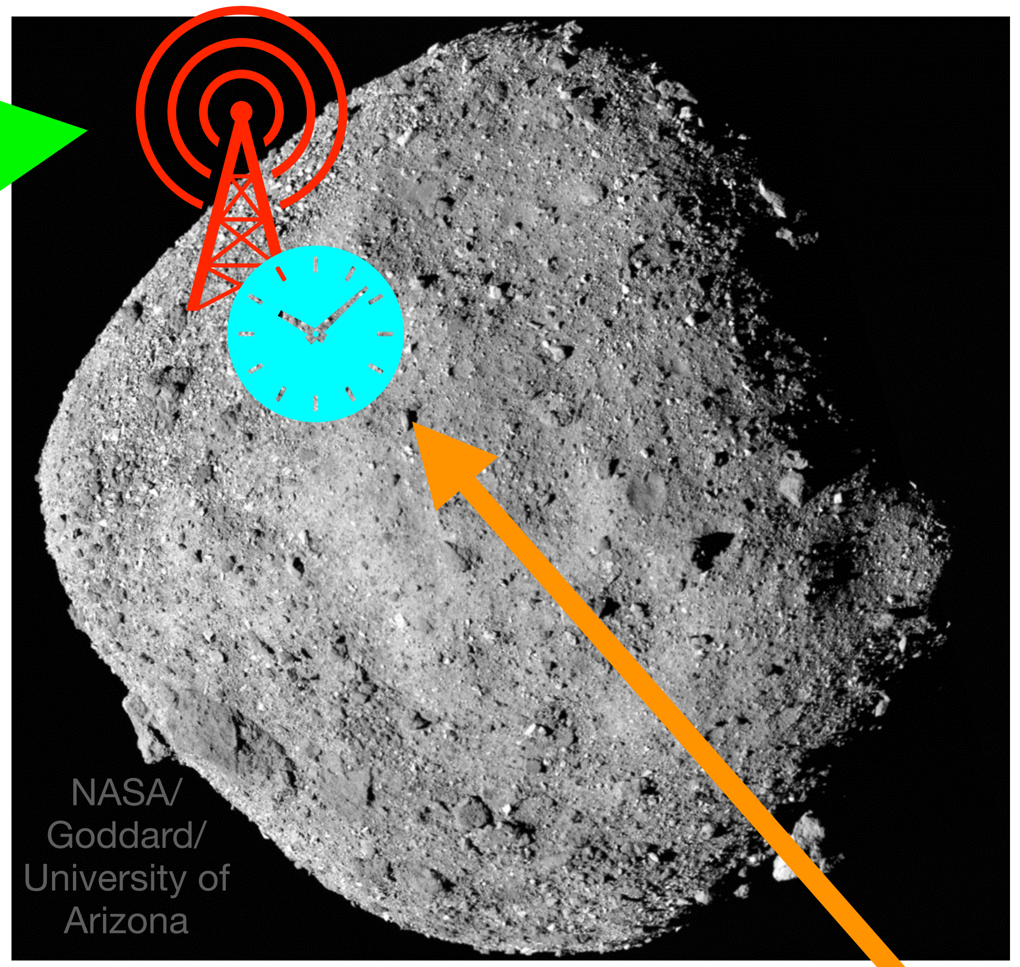
Ranging: park base stations (clock + emitter/receiver) on good candidates and range by, e.g., radio or laser timing

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

Radio or laser ranging



Base station:
emitter/receiver
atomic clock



Base station:
emitter/receiver
atomic clock

Candidates and missions

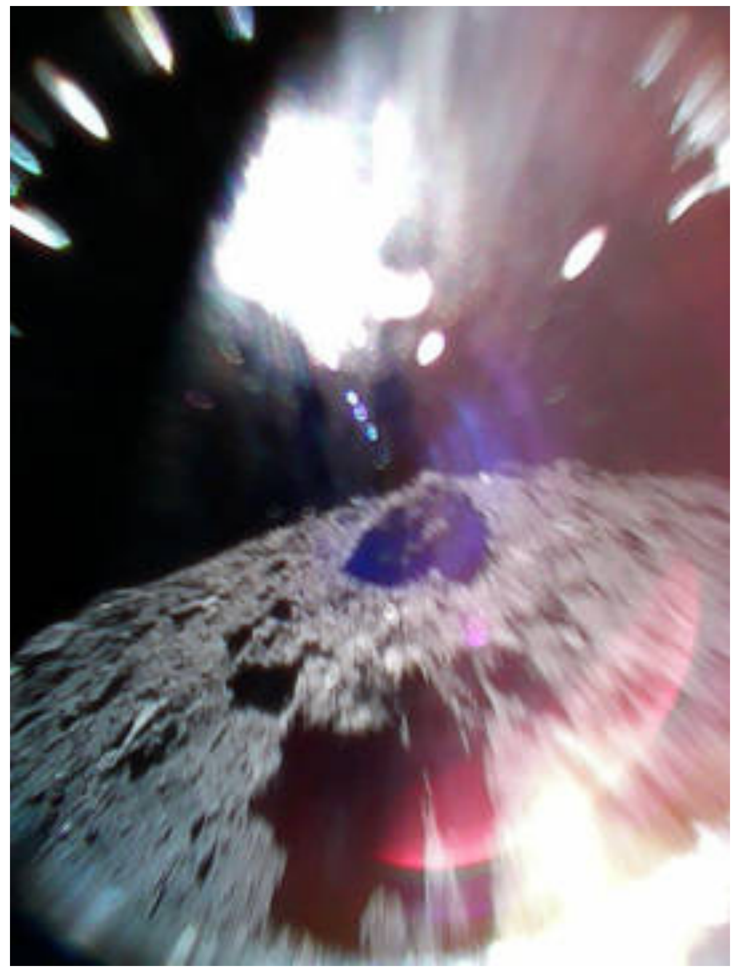
NASA JPL Small-Body Database

Asteroid	a [AU]	D [km]	T_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

Candidates and missions

NASA JPL Small-Body Database

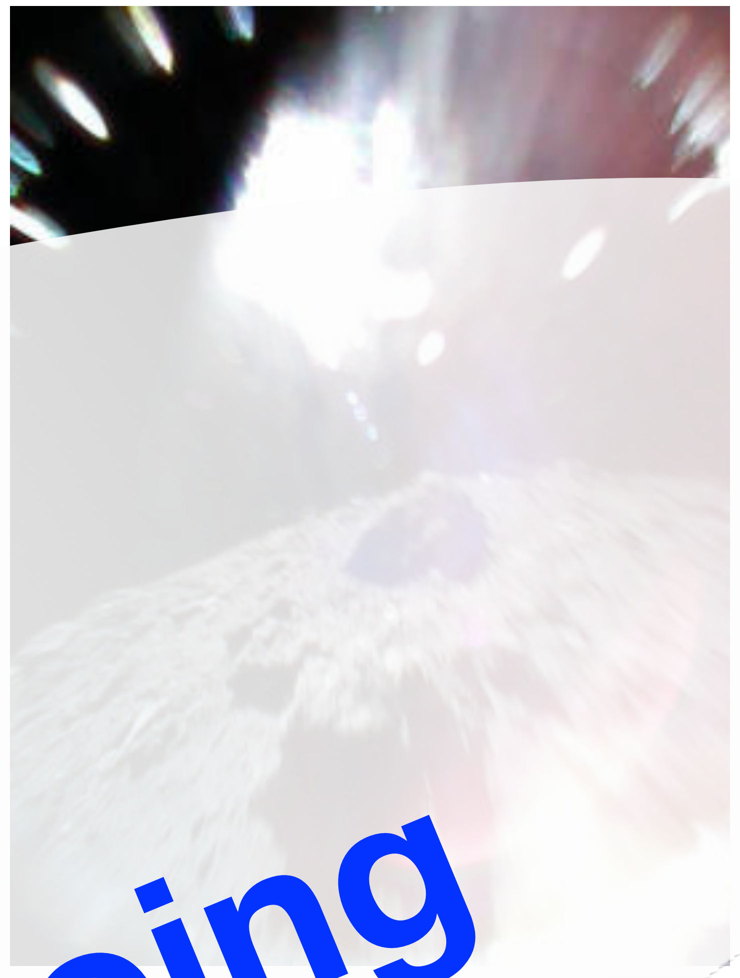
Asteroid	a [AU]	D [km]	T_rot [hrs]
433 Eros	1.46	16.8	5.3
1627 Ivar	1.86	9.1	4.8
2064 Thomsen	2.18	13.6	4.2
6618 Jimsimons	1.87	11.5	4.1

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

Asteroid candidates exist

Missions to asteroids are ongoing

Hayabusa2 @ Ryugu



JAXA

OSIRIS-Rex @ Bennu

Note: Bennu is a “rubble pile”

NASA/Goddard/University of Arizona

Noise sources

- Gravitational pull of large bodies (planets, moons) - ephemeris and $G_N M_{\text{obj}}$ known

- Solar intensity fluctuations
- Solar wind fluctuations
- Thermal cycling
- Noise at rotational period
- GGN from other $\sim 10^6$ asteroids in Main Belt ⟵ M.F., P.W. Graham, and S. Rajendran. *Phys. Rev. D* ***103**, 103017* (2021) [2011.13833].
- Seismics, charging, magnetic forces and torques, collisions, tidal deformation, etc.

- Clock noise
- Link (shot/thermal) noise

- etc…

… let’s walk through (some of) these for an example asteroid

Solar intensity fluctuations

Solar radiation pressure gives CoM a DC acceleration

$$a \sim \frac{\boxed{P_\odot}}{c}\left(\frac{r_\oplus}{\boxed{r}}\right)^2 \frac{\boxed{A_{\rm ast}}}{M_{\rm ast}} \sim 10^{-14}\,\mathrm{m/s^2} \times \left(\frac{1.5\mathrm{AU}}{r}\right)^2 \times \left(\frac{8\mathrm{km}}{R_{\rm ast}}\right) \times \left(\frac{2.5\mathrm{g/cm^3}}{\rho_{\rm ast}}\right)^{-1}$$

… actually modulated at the rotation period, but this is high-frequency ($\sim 3 \times 10^{-5}\,\mathrm{Hz}$) for us. **BIG**, but out of band.

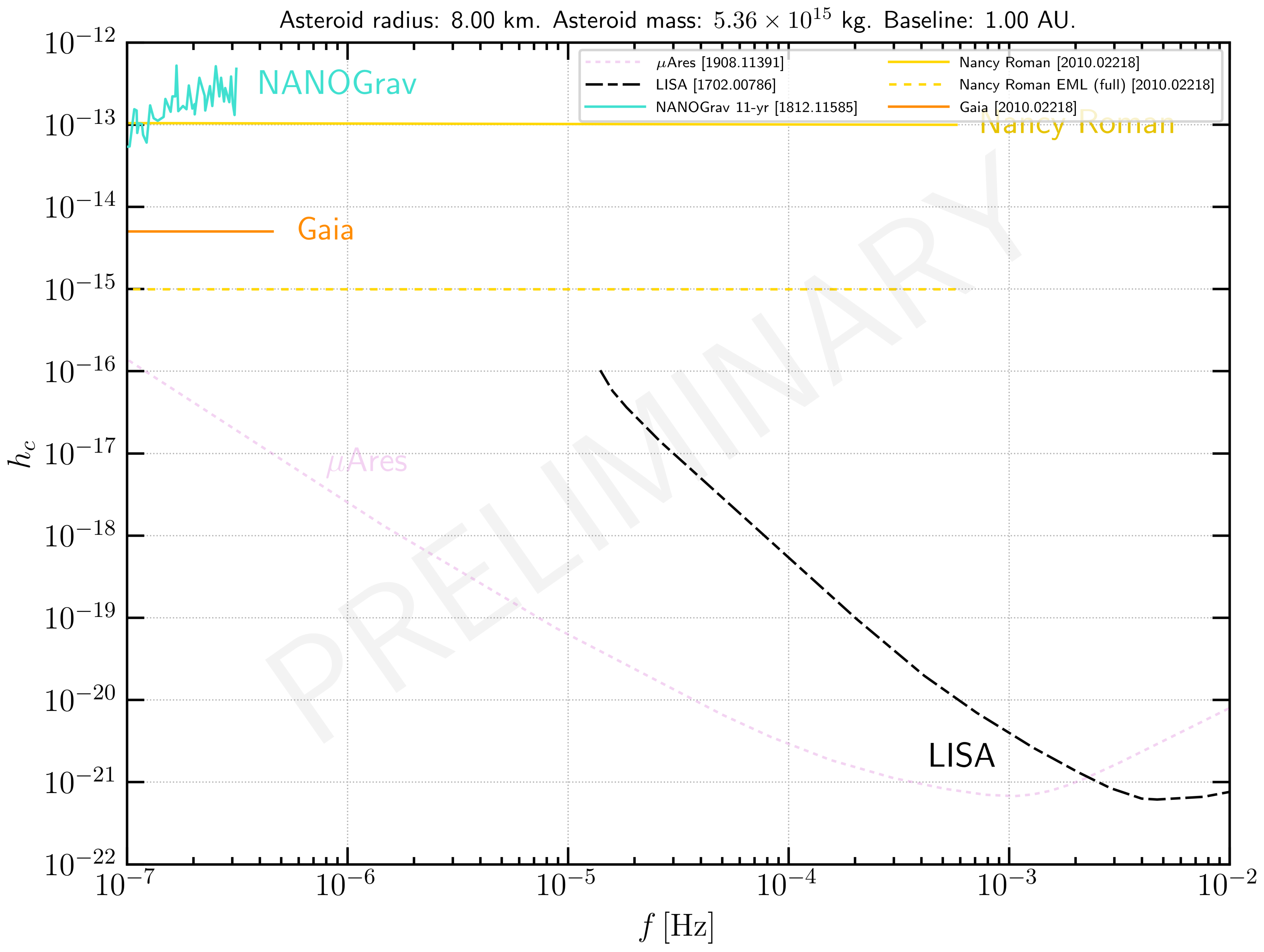
Actually care about the solar intensity fluctuations that are *<u>in-band</u>*:

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

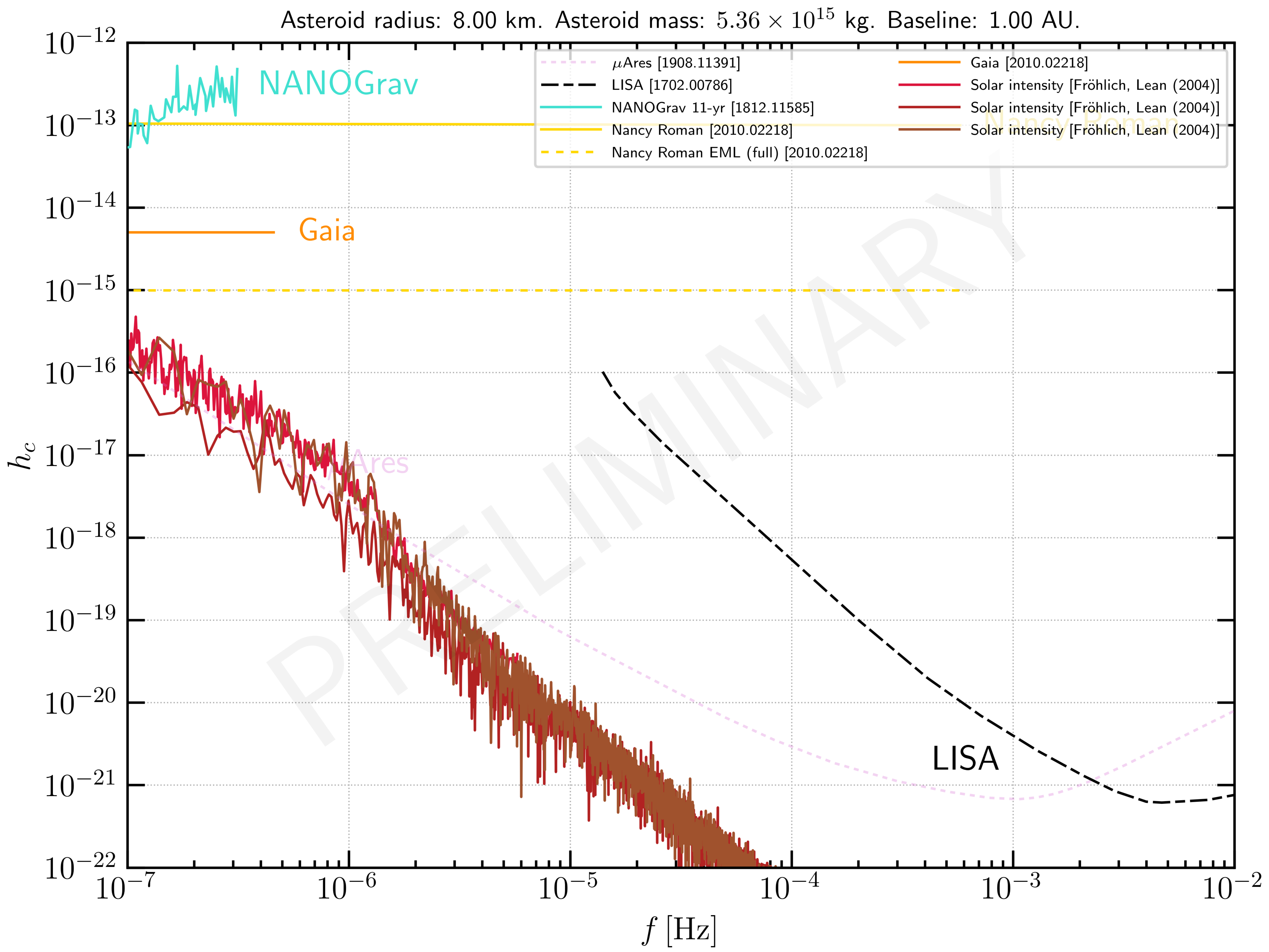
$$h_c \sim (2\pi f)^{-2} L^{-1} \sqrt{f S_a(f)}$$

MEASURED FRACTIONAL SOLAR PSD

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

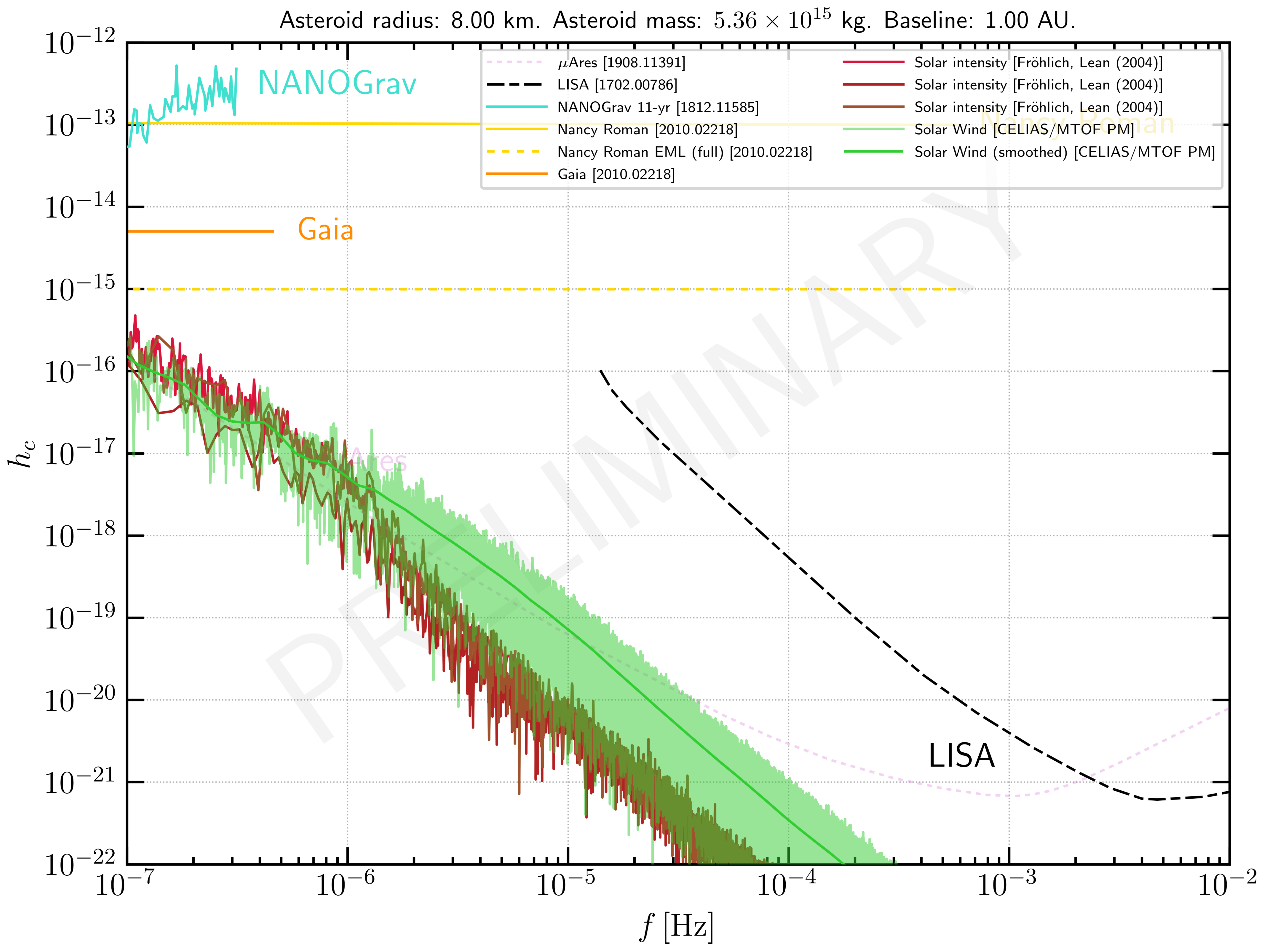


Existing or projected approaches in the μHz band



Solar intensity fluctuations

8km spherical asteroids at 1.5AU from the Sun, assuming fixed 1AU baseline (for argument)



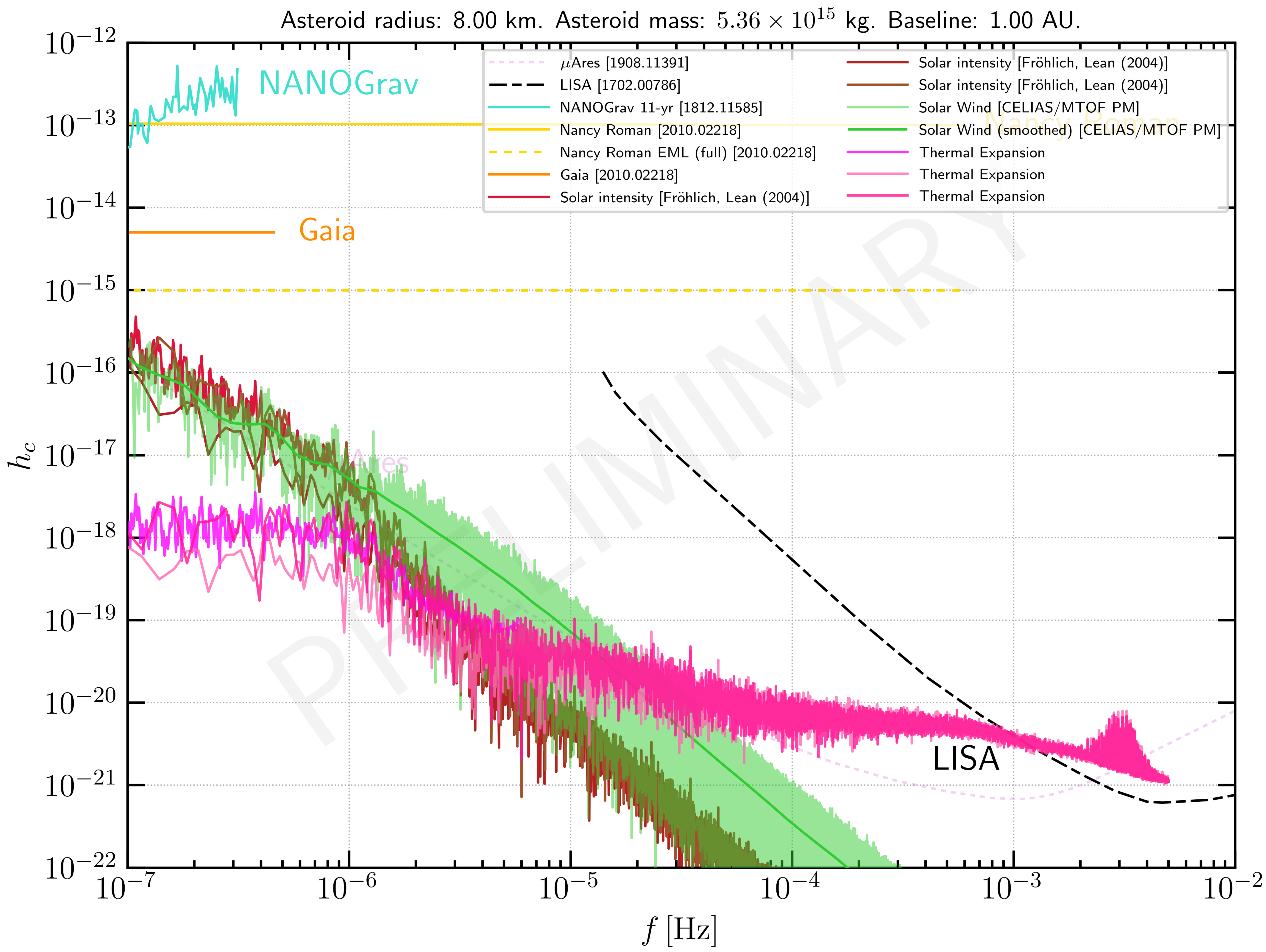
Solar wind fluctuations

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

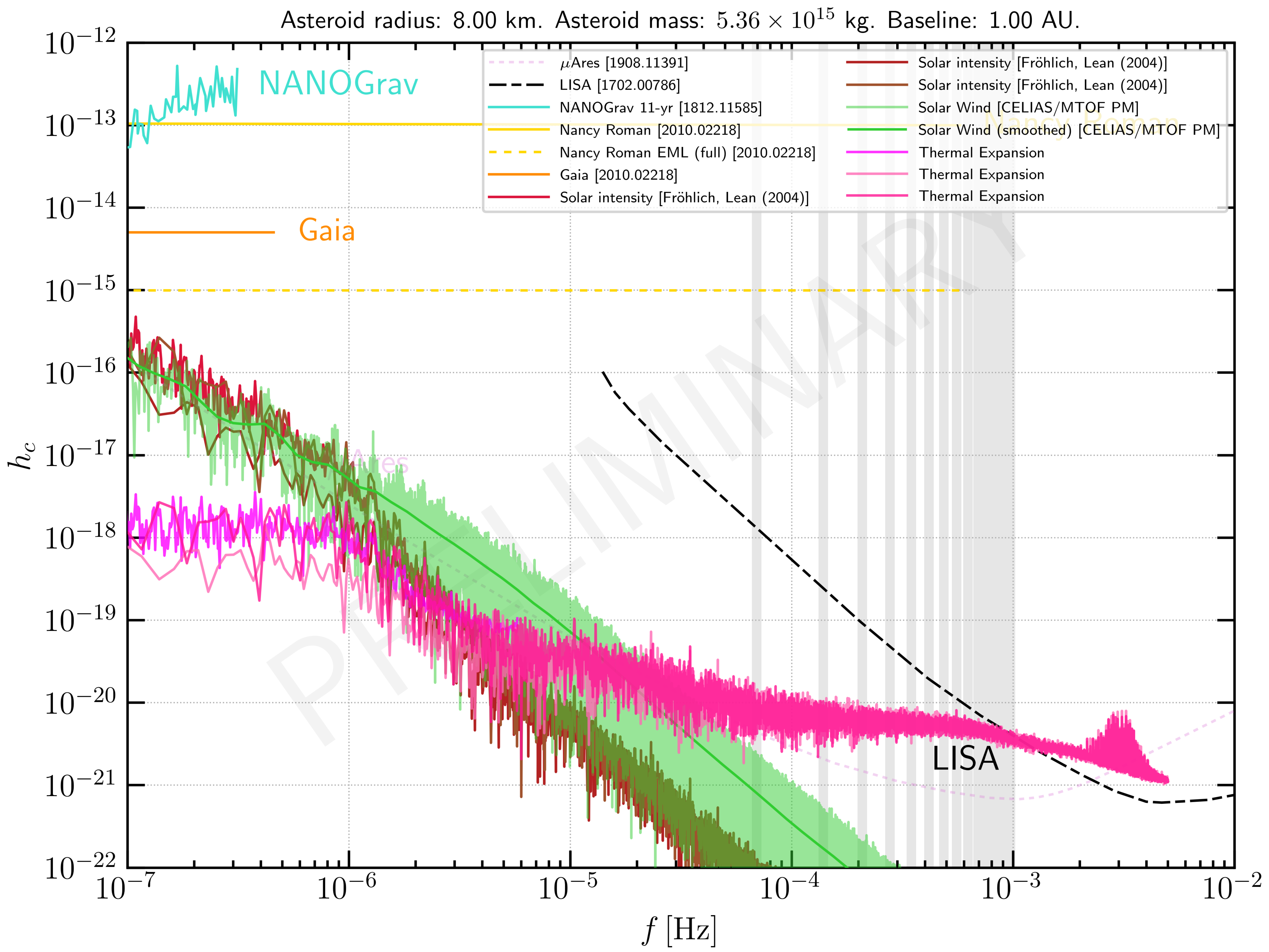
$$d_{\text{th.}} \sim 1\,\text{m} \times \sqrt{\mu\text{Hz}/f}$$

of the asteroid

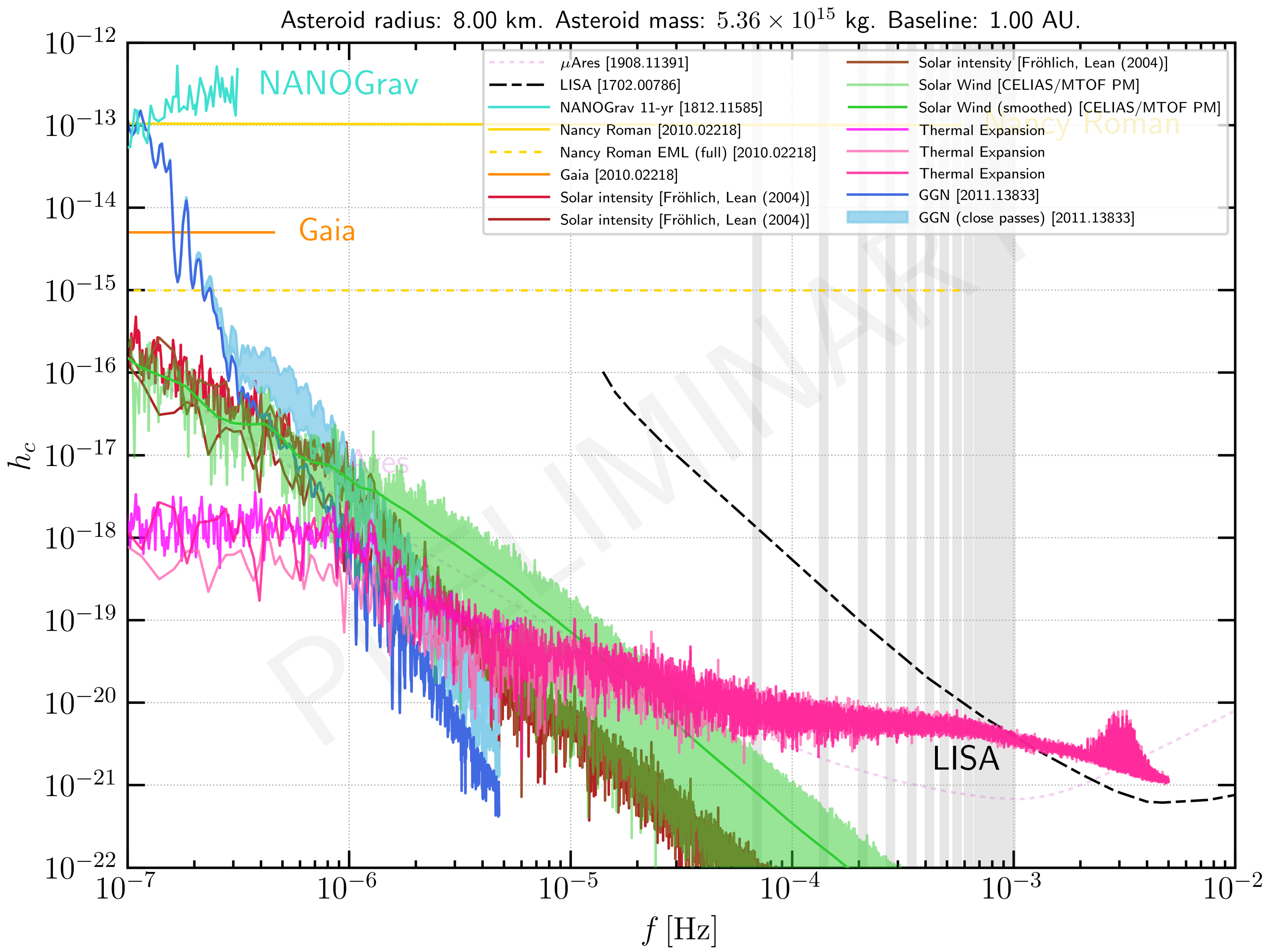
(rock estimate - conservative, since regolith is a blanket)

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

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



Severe noise at rotational period(s)



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

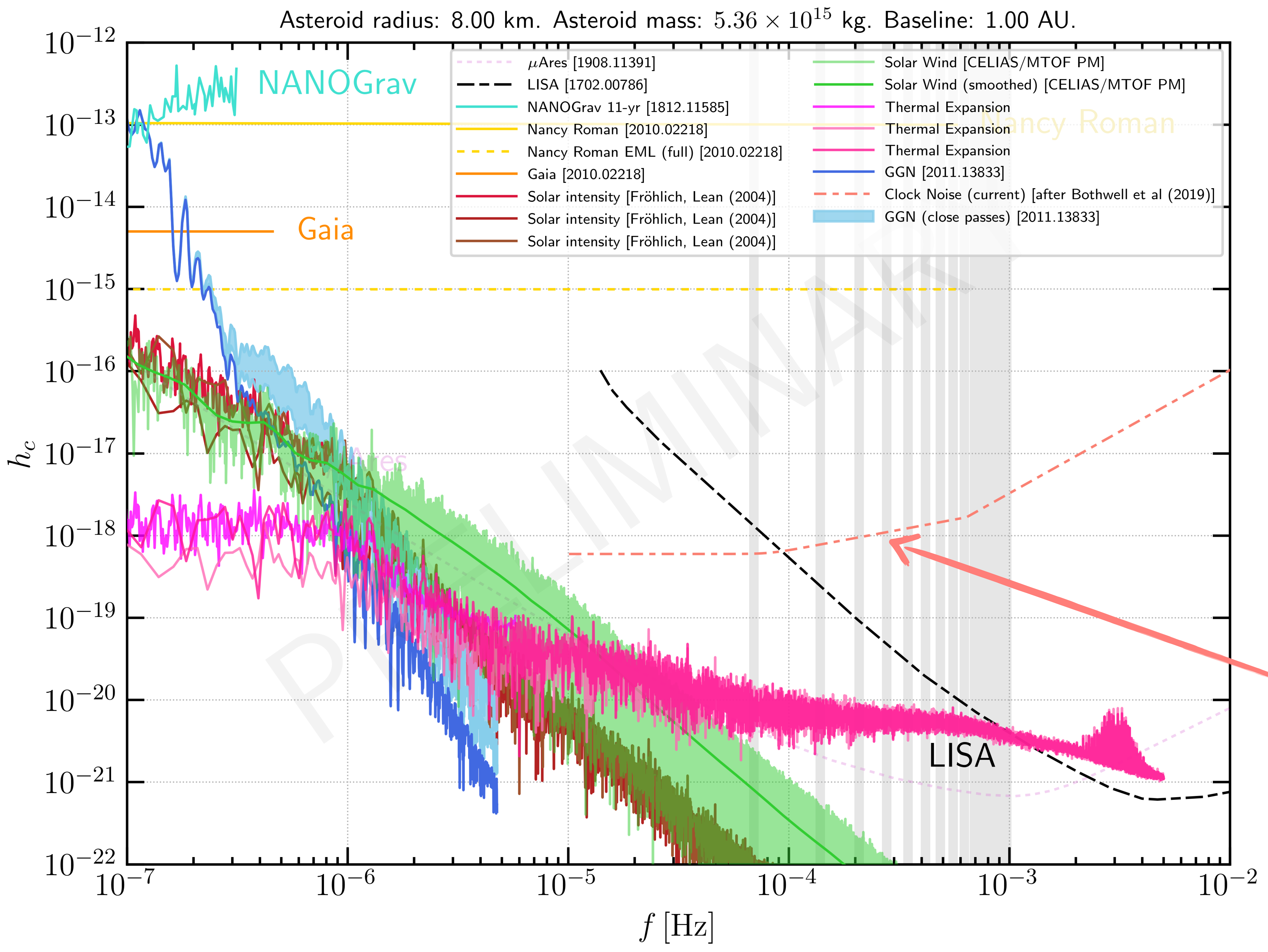
Note: also get cut off severely by uncontrolled relative motion of asteroids around orbital frequencies.

Many other acceleration noise sources estimated, and appear to be sub-dominant*

A word or two on seismic noise

- Severe problem for Earth-based GW detection
    - But Earth has a tectonic motion, a molten core, etc.
- Many reasons to be optimistic for asteroids:
    - Ancient, dead rock. No plate motion, no residual heat.
    - Pick asteroids that are ~ solid (i.e., not unstable rubble piles like 101955 Bennu)
    - 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
    - In-situ seismic / plastic deformation measurements should be made on asteroids prior to a full mission: e.g., seismometers; global optical relative-motion monitoring of, e.g., corner cubes deployed on surface
- <u>Strongly motivates inclusion of seismic experiments on future asteroid missions</u> (already motivated by internal structure studies [e.g., APEX mission concept])

Clock Noise



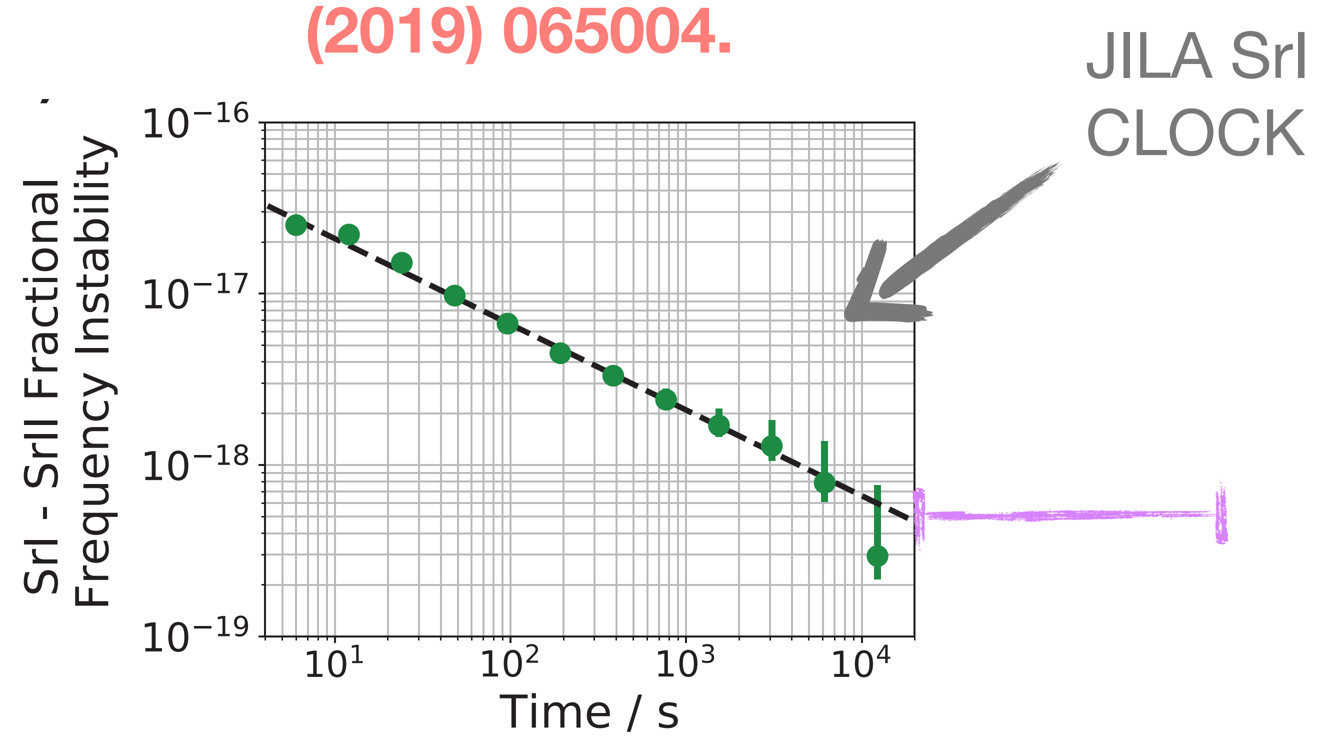
Ranging is by, e.g., return-trip pulse timing.

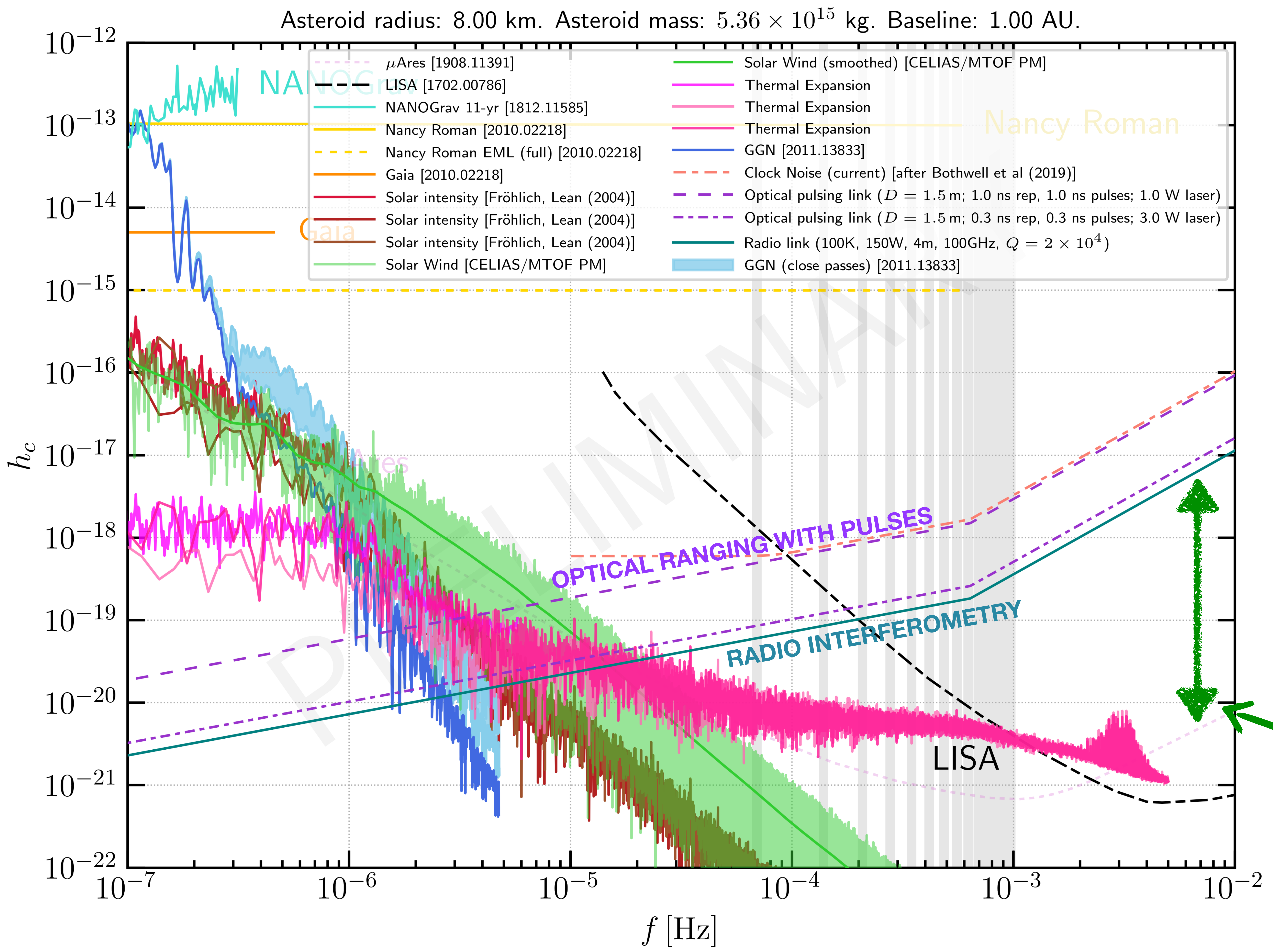
Existing ground-based clocks are already sufficient for excellent reach.

Clock accuracy improvement extremely rapid. Probably not a limit.

Further motivates space-qualification of atomic clocks.

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





Link Noise

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

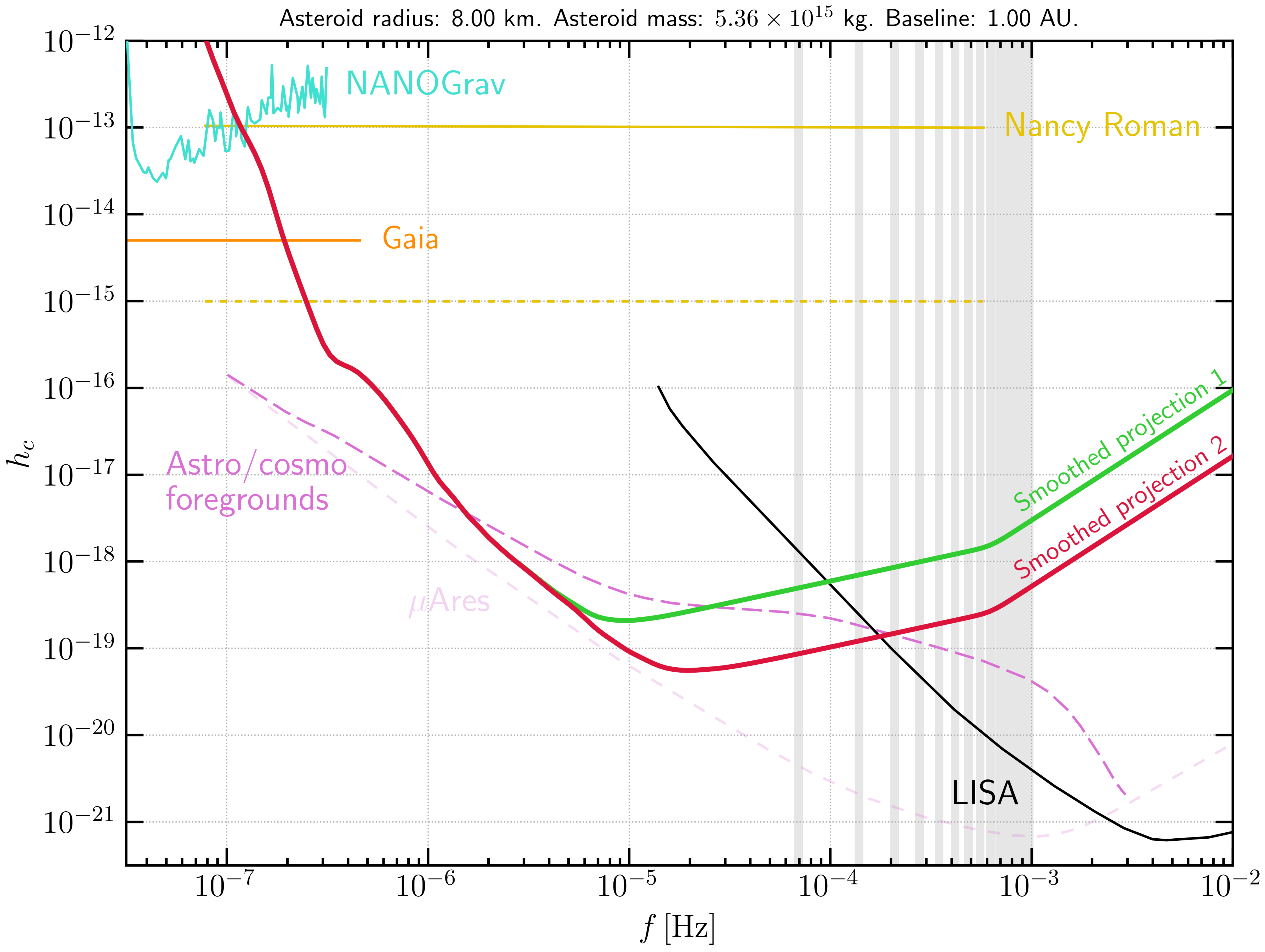
Shot noise of laser pulsing link OR thermal noise from radio interferometric link.

Exemplar curves shown.

Asteroids are (obviously) **not** in formation flight. LISA-class optical 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!