Gravitational Waves

and New Physics

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Stanford

Topics

1. Atomic Clocks and Gravitational Waves at ~ μHz

2. Millicharged Particles and Trapped Ions

PRELIMINARY!

Atomic Clocks and Gravitational Waves at ~ 1-10 μHz

(PRELIMINARY)

with

Michael Fedderke

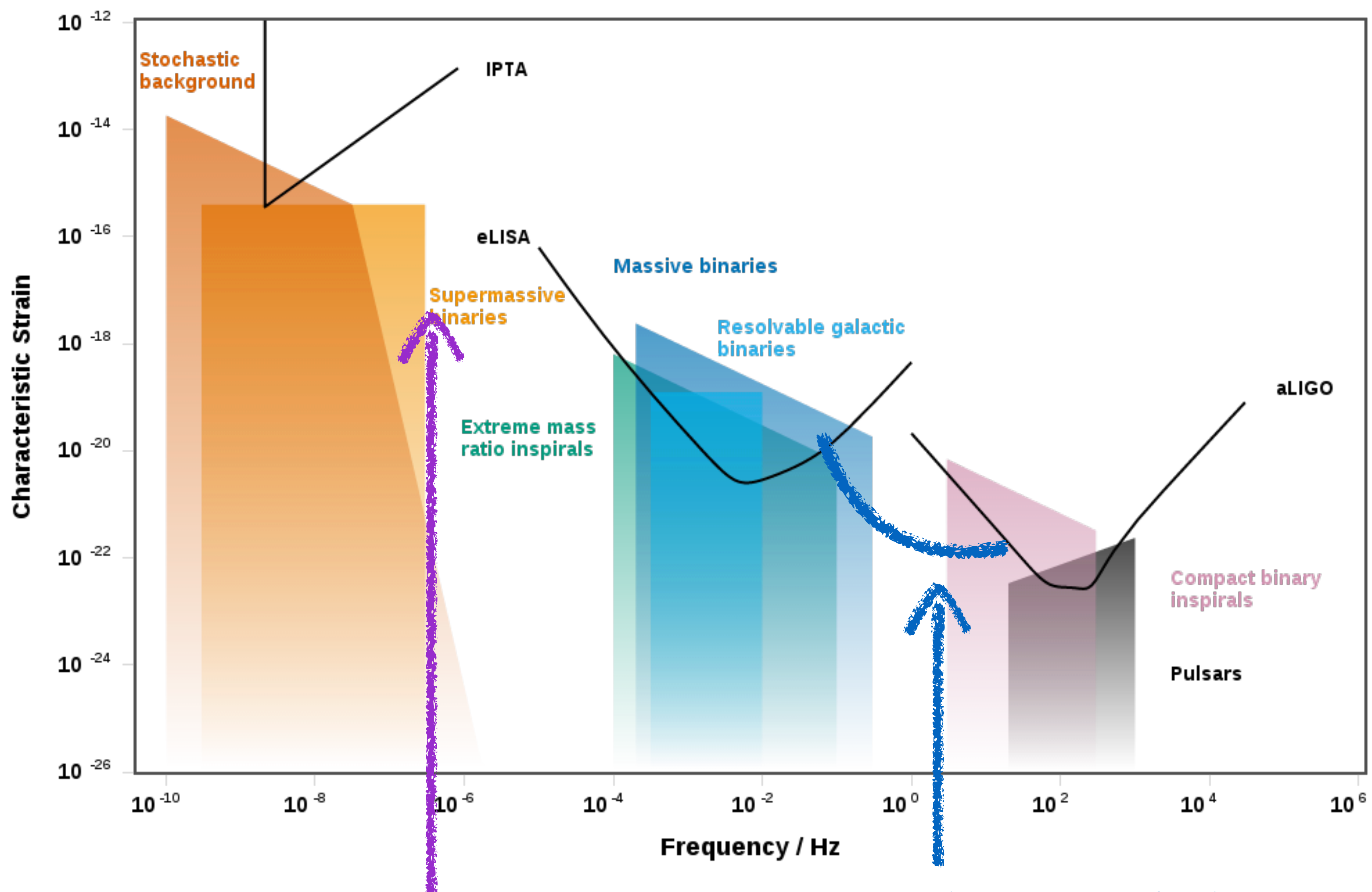
Surjeet Rajendran

Gravitational Spectrum

Gravitational waves will be major part of future of astronomy, astrophysics and cosmology

Crucial to observe as many bands as possible!

many observatories operating or planned from ~ nHz to kHz



open band
~ 10^{-7} Hz - 10^{-4} Hz

atoms (MAGIS, clocks, MIGA, AION...)

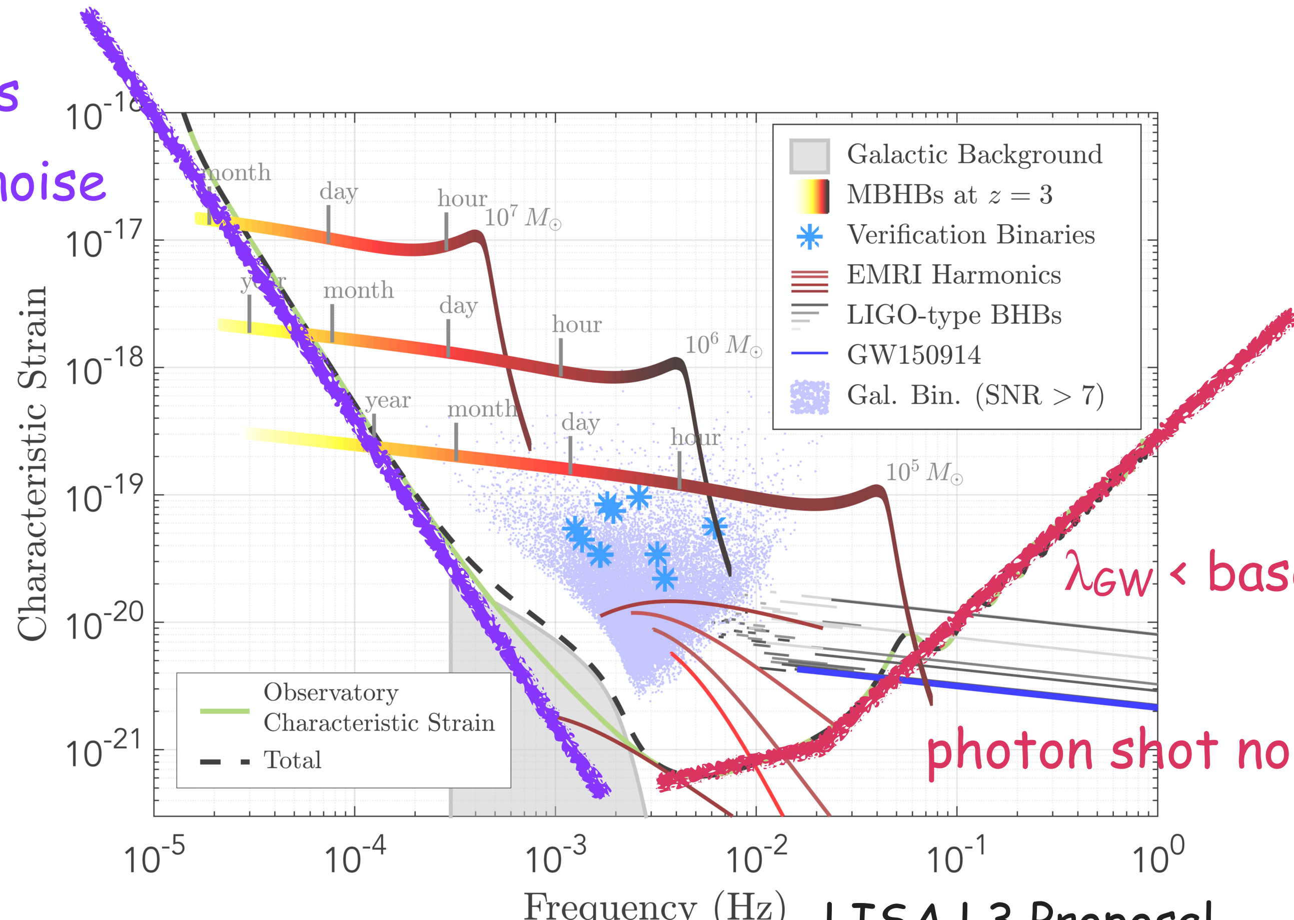
Important to consider all possible detection techniques to cover the entire spectrum

Why the "μHz Gap"?

Why doesn't LISA reach lower frequencies?

proof mass acceleration noise

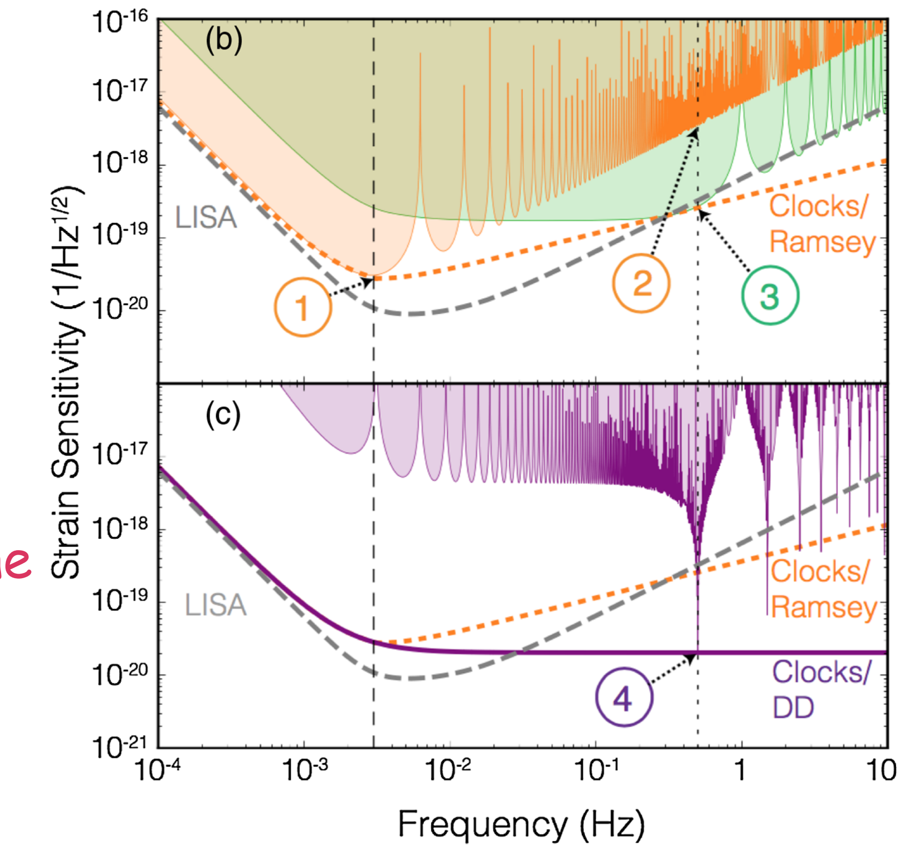
rises at low frequency



λ_{GW} < baseline

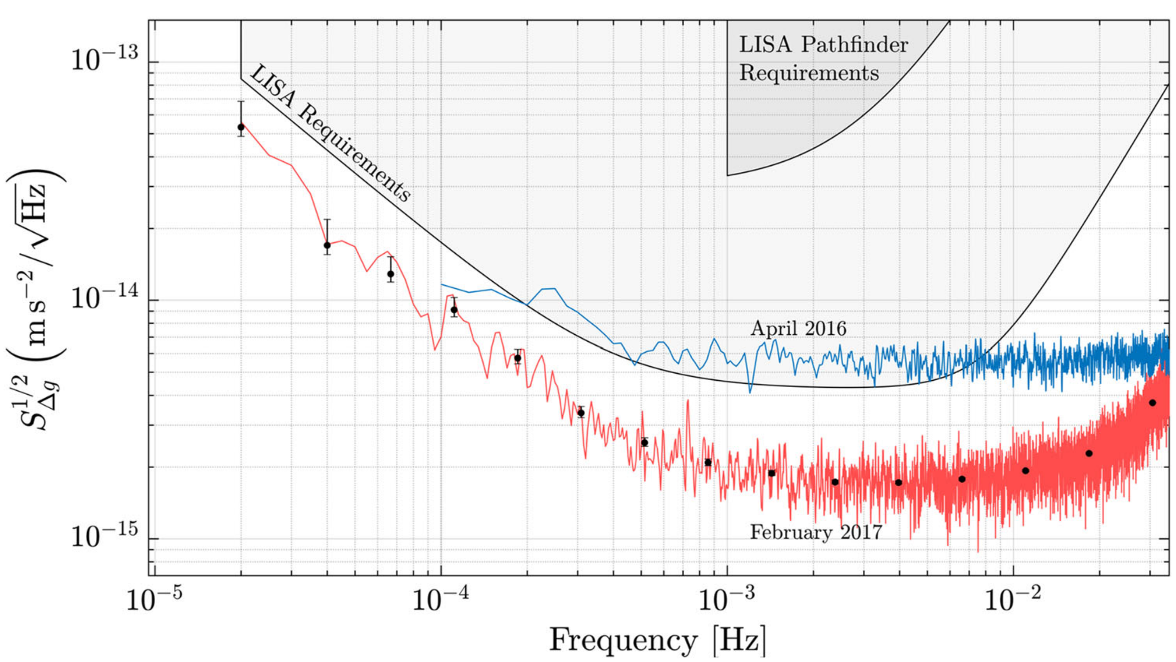
photon shot noise

LISA L3 Proposal



Kolkowitz, Pikovski, Langellier, Lukin, Walsworth, Ye, PRD (2016)

measured:



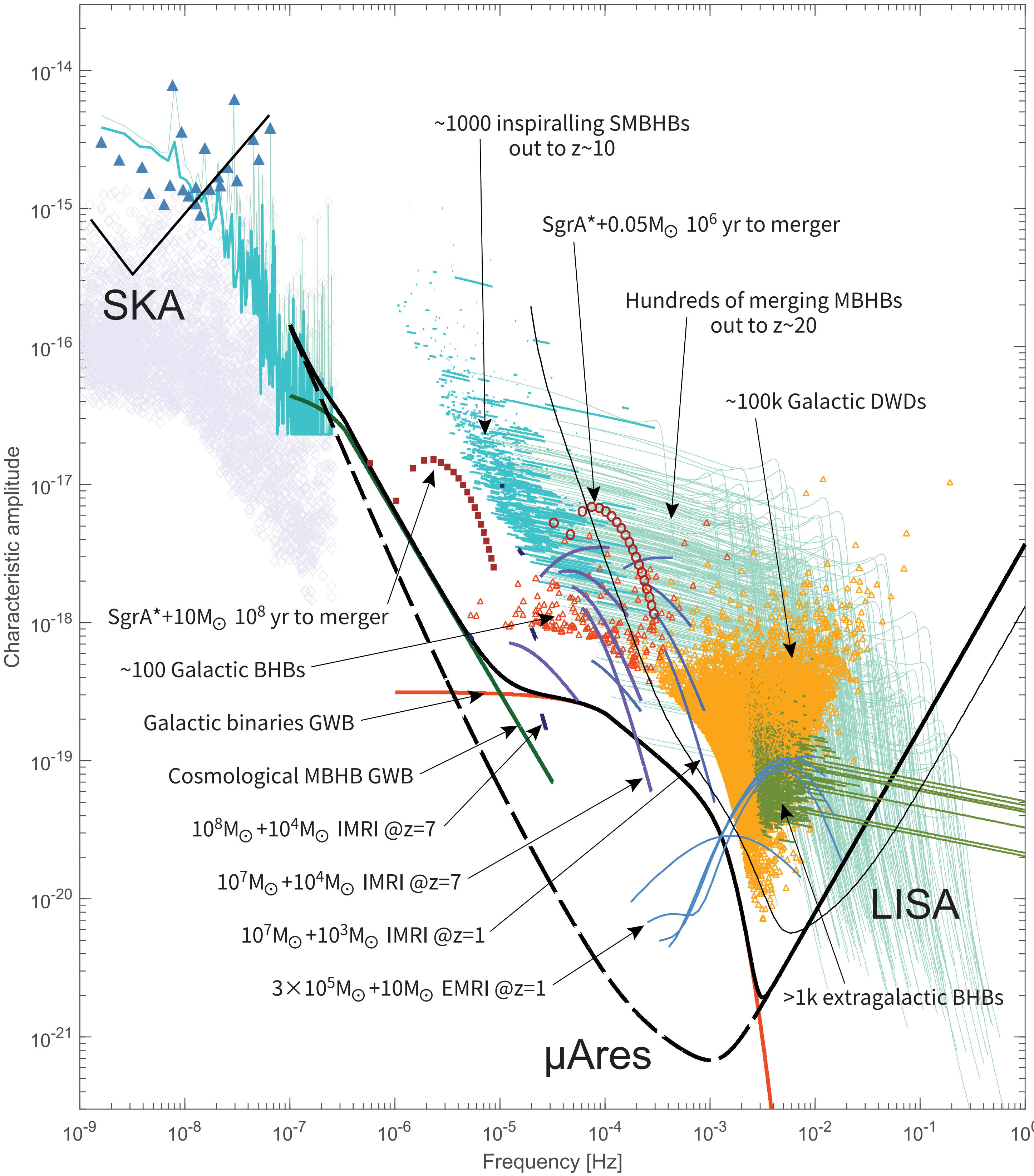
LISA Pathfinder PRL (2018)

How could you reach lower frequencies?

- Decrease acceleration noise (e.g. μAres concept)
- Extend arm length (μAres)
- Use astrophysical proof mass, e.g. pulsar timing or lunar laser ranging approach

GW Science Around μHz

μAres 1908.11391



μAres concept a LISA-like configuration with L ~ 1 AU arm lengths

assumes acceleration noise flat at low frequencies, not rising as 1/f

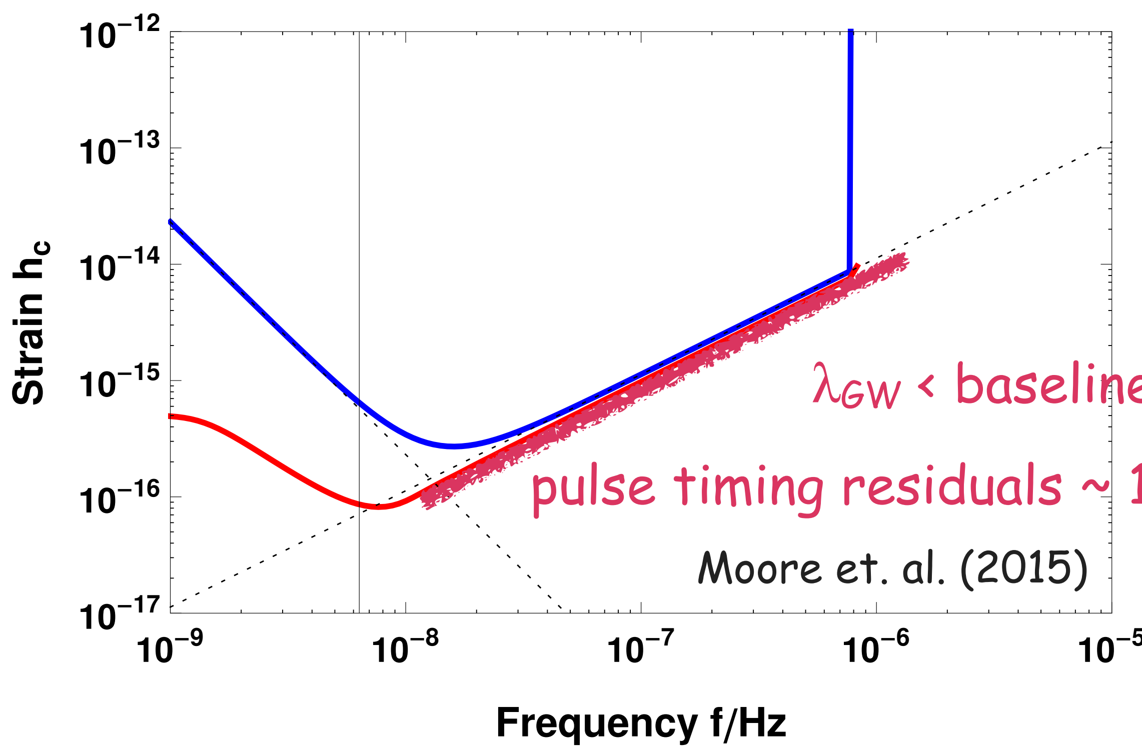
Other ways to observe this band?

Many sources in ~ 10^{-7} Hz - 10^{-4} Hz band!

Astrophysical Proof Masses

Why doesn't Pulsar Timing reach higher frequencies?

Pulsars very heavy so excellent inertial proof masses (and clocks)



λ_{GW} < baseline ➜ GW signal $\propto \lambda_{\mathrm{GW}}$

pulse timing residuals ~ 10 ns

baseline is "too long" or really insufficient timing of pulses for higher frequency band

want: shorter baseline for good SNR of pulses, man-made clock + pulses

Lunar laser ranging uses Earth-Moon system

but Earth has atmosphere + seismic noise (plate tectonics…)

what can we use?

So what can we use?

Bigger than a satellite, smaller than the Earth so no atmosphere or plate tectonics:

can we use asteroids?

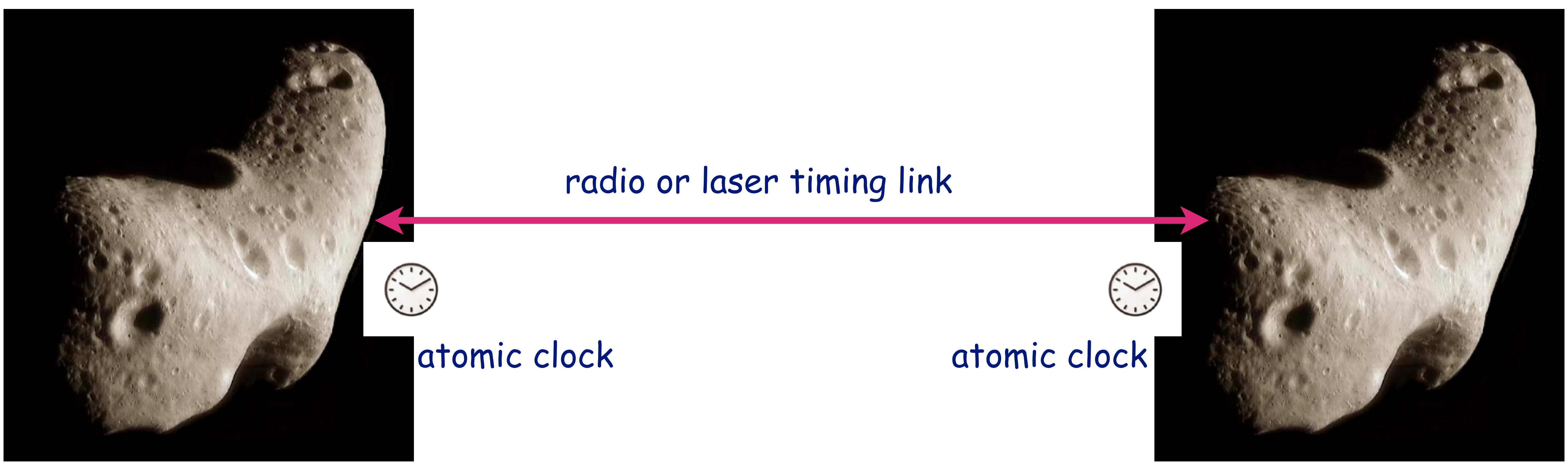
Will evaluate asteroids as inertial proof masses

for gravitational wave detection

in particular will evaluate acceleration noise for asteroids

will argue it can naturally be much lower than human-made proof masses in this frequency band

toy concept for a full GW experiment (others possible too):



433 Eros

focus on ~ 10 km asteroids orbiting ~ 2 AU with baseline ~ AU

Some Example Asteroids

from NASA asteroid database:

results

full_name	a (AU)	e	per_y	n_dop_obs_used	H	diameter (km)	albedo	rot_per
433 Eros (A898 PA)	1.458045729	0.222951265	1.760617117	2	10.4	16.84	0.25	5.27
1627 Ivar (1929 SH)	1.863272945	0.396783058	2.543448329	1	12.7	9.12	0.15	4.795
2064 Thomsen (1942 RQ)	2.178626927	0.329840411	3.215751662		12.6	13.61	0.0549	4.233
3353 Jarvis (1981 YC)	1.863022742	0.084636421	2.54293604		13.7	10.528	0.049	202
6618 Jimsimons (1936 SO)	1.874978569	0.044348412	2.56745396		13.4	11.506	0.07	4.142

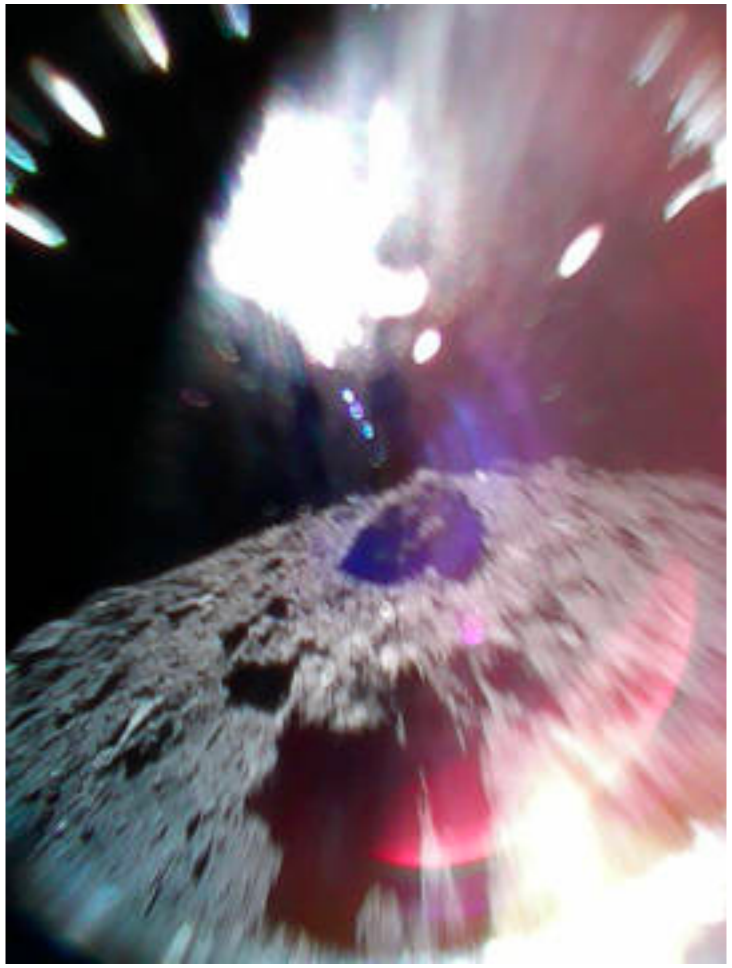
Human Exploration of Asteroids

Have landed on asteroids many times:

Body	Mission	Country/Agency	Date of landing/impact
Eros	NEAR Shoemaker	USA	12 February 2001
Itokawa	Hayabusa	Japan	19 November 2005
			25 November 2005
Ryugu	Hayabusa2	Japan	21 September 2018
		France / Germany	3 October 2018
		Japan	21 February 2019
			5 April 2019
			April 2019
			11 July 2019
			October 2019
Bennu	*OSIRIS-REx*	USA	20 October 2020

Wikipedia

even "driven" rovers,
collected samples…



162173 Ryugu

Much ongoing interest in landing on asteroids

I'll mainly focus on evaluating asteroids as proof masses,
not on (challenging) engineering aspects of rest of mission

Asteroid Acceleration Noise

Gravitational perturbations from planets etc. are low frequency (and well-known)

A major remaining, fluctuating, force is radiation pressure from sun. To estimate:

reduced by larger and farther asteroid

$$a \sim \frac{A_{\rm ast}}{M_{\rm ast}} P_\oplus \left(\frac{r_\oplus}{r_{\rm ast}}\right)^2$$

solar intensity fluctuations measured

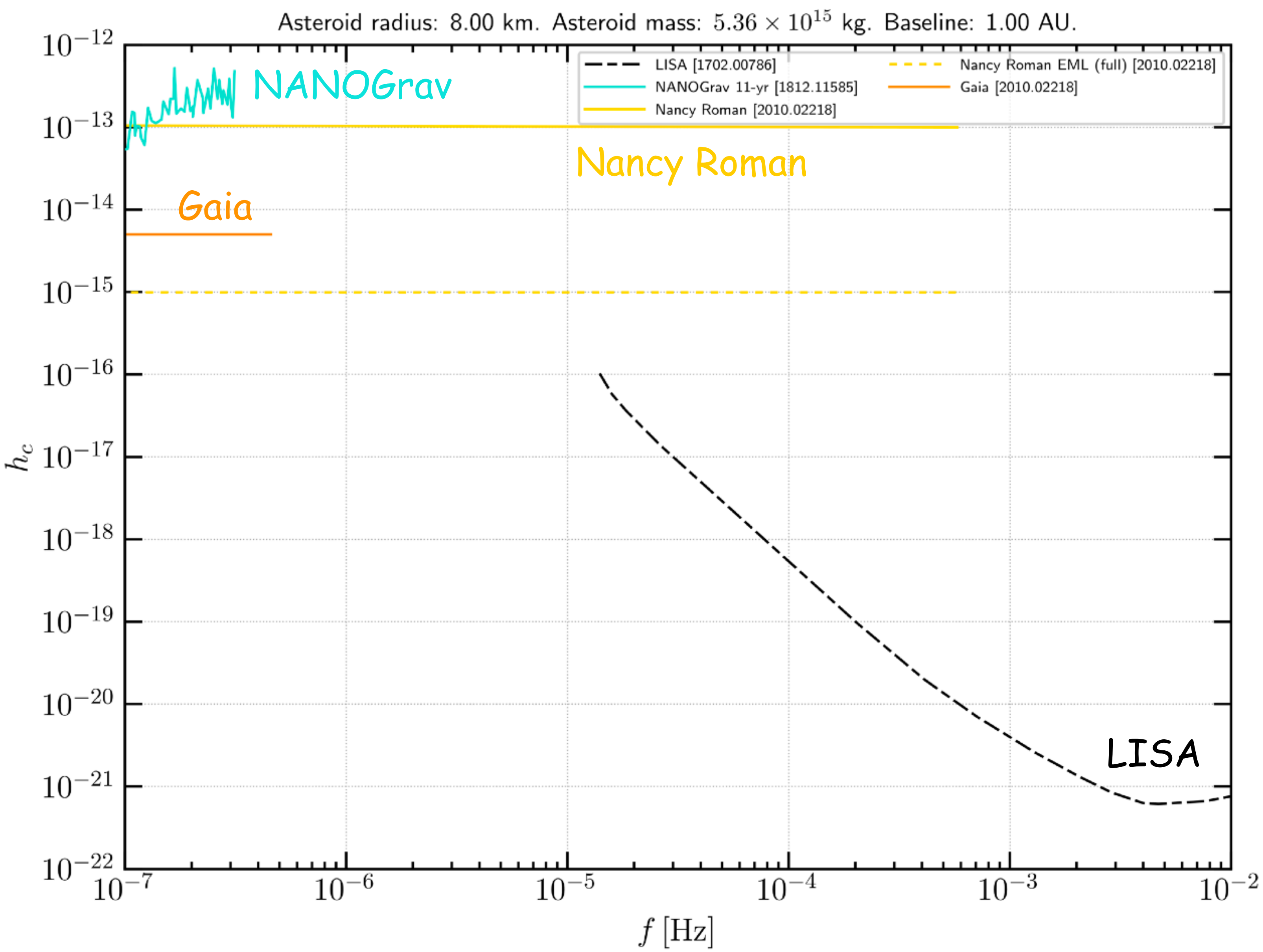
at relevant frequencies

strain ASD: $$\sqrt{S_h(f)} = \left(\frac{3\epsilon \bar{P}_\oplus}{4\rho_{\rm ast} Rc\cdot(2\pi f)^2 L}\left(\frac{r_\oplus}{r_{\rm ast}}\right)^2\right)\sqrt{S_{\hat{P}}(f)}$$

albedo/area fluctuations at rotation period (out of band)

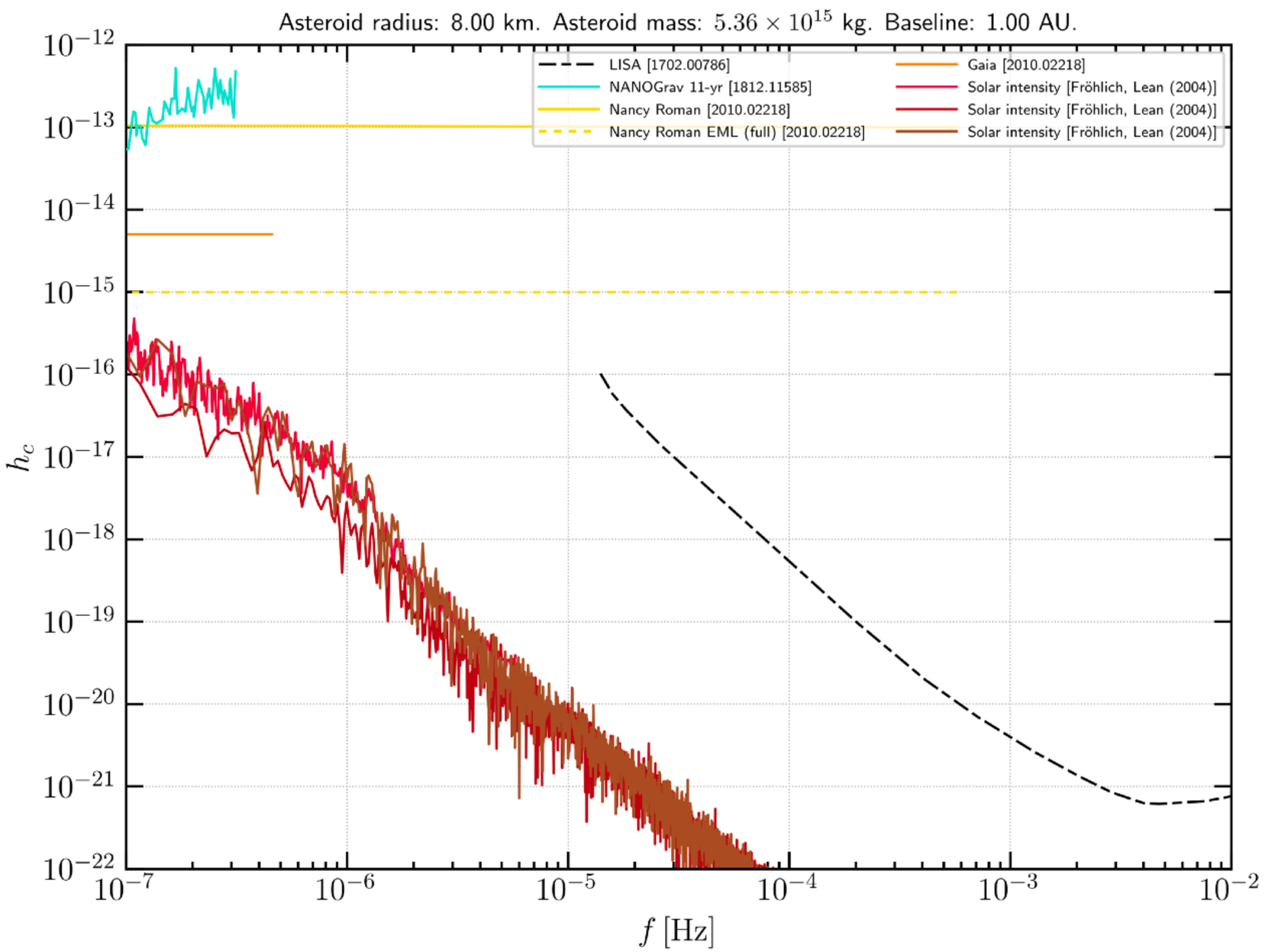
diameters > 1 km give sufficient noise suppression

Unexplored GW Band



Solar Intensity Acceleration Noise

Measured solar intensity fluctuations, applied to example asteroid



strain ASD:

$$\sqrt{S_h(f)} = \left(\frac{3\epsilon \bar{P}_\oplus}{4\rho_{\text{ast}} Rc \cdot (2\pi f)^2 L} \left(\frac{r_\oplus}{r_{\text{ast}}} \right)^2 \right) \sqrt{S_{\hat{P}}(f)}$$

measured solar intensity PSD

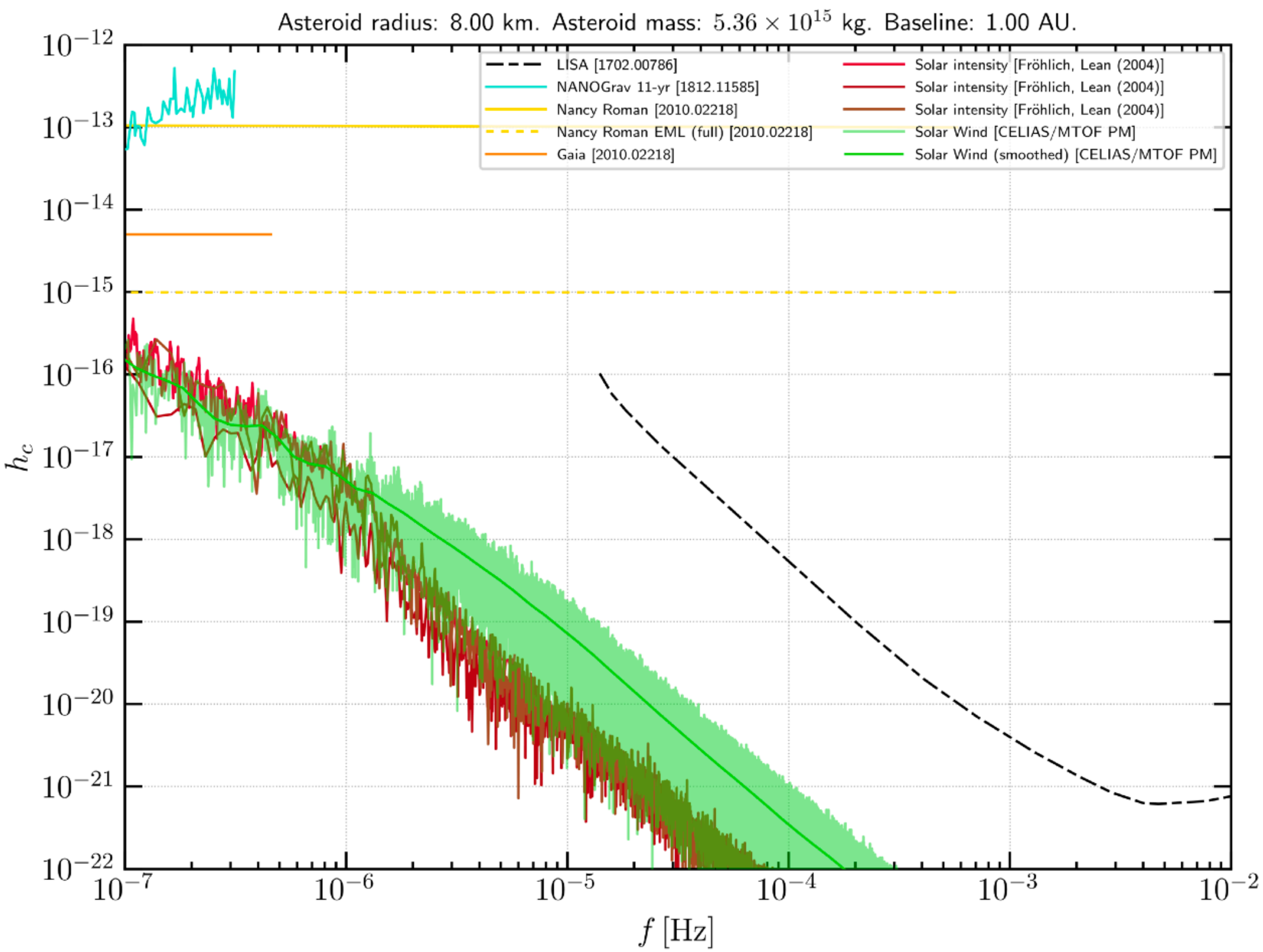
Fröhlich & Lean (2004)

solar wind has smaller average force but larger in-band variation,

estimate similarly:

Solar Wind Acceleration Noise

Measured solar wind fluctuations, applied to example asteroid



strain ASD:

$$\sqrt{S_h(f)} = \frac{3\epsilon m_p}{4R\rho_{\rm ast}(2\pi f)^2 L}\sqrt{S_\Omega(f)}$$

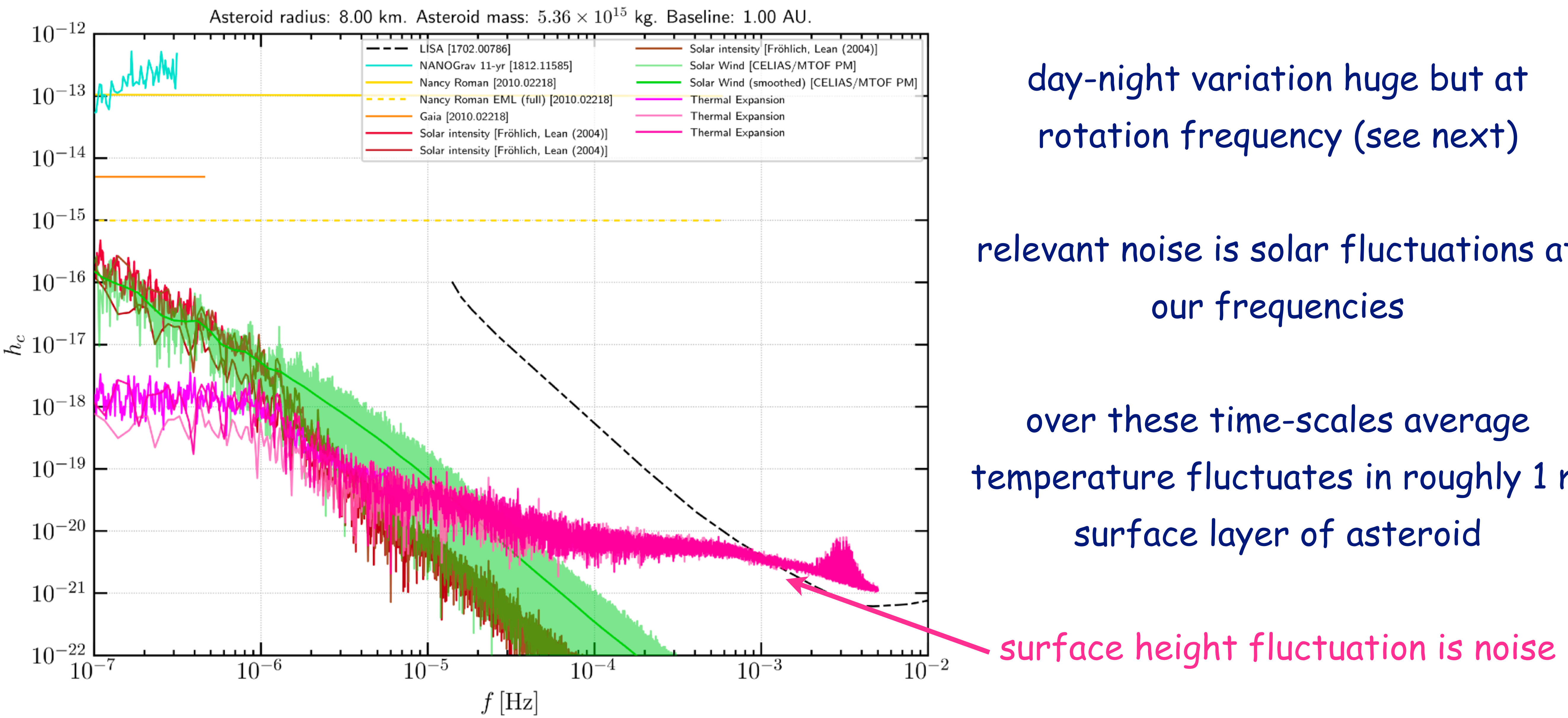
measured solar wind PSD

CELIAS, MTOF monitor on SOHO satellite

$$\Omega = n_p v_p^2$$

Thermal Noise

Solar intensity fluctuations cause variable heating ➜ thermal expansion noise



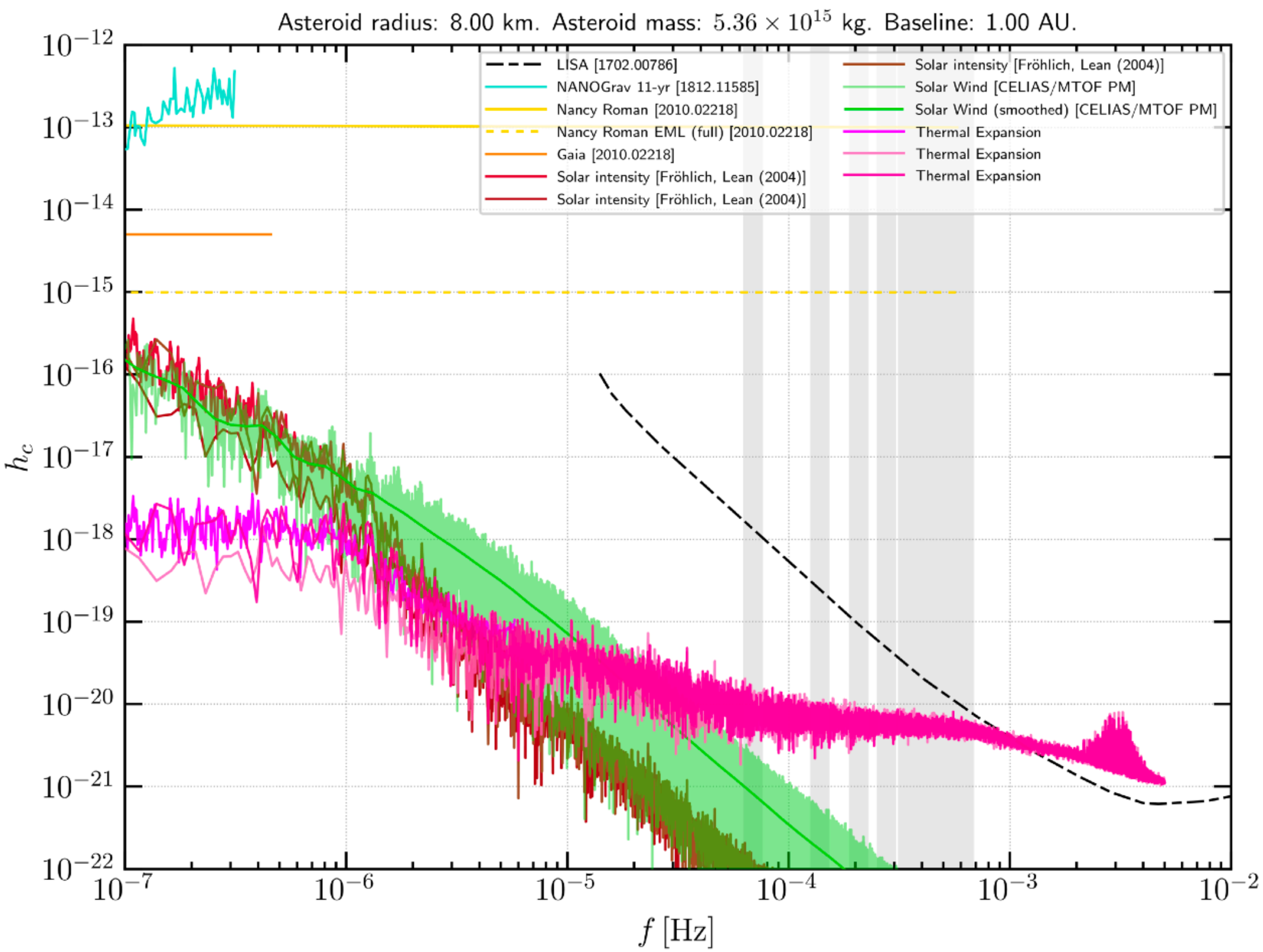
day-night variation huge but at rotation frequency (see next)

relevant noise is solar fluctuations at our frequencies

over these time-scales average temperature fluctuates in roughly 1 m surface layer of asteroid

Rotation Noise

Asteroid rotation periods generally ~ few hours



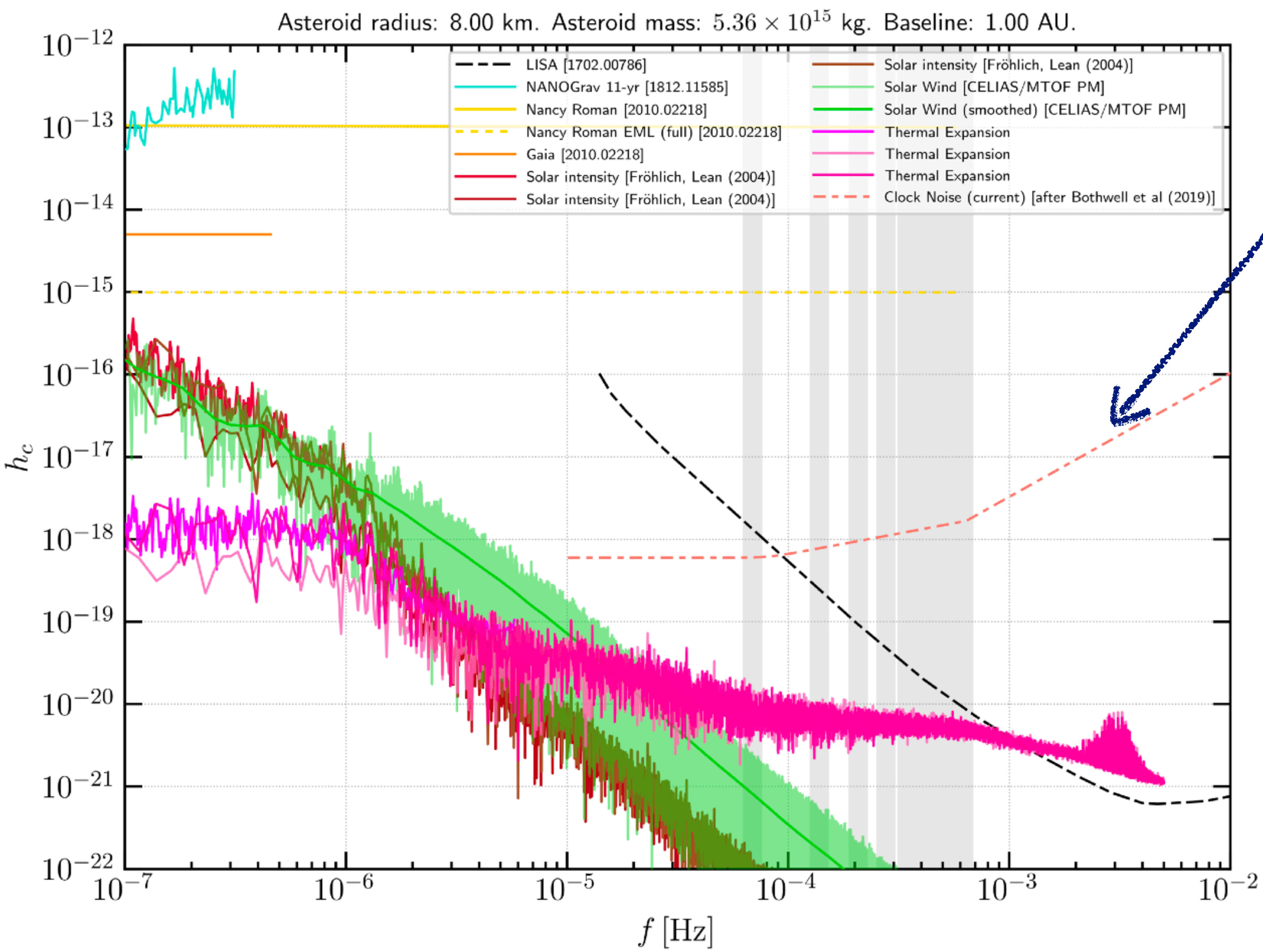
removes higher frequency bands

many other acceleration noise sources (e.g. collisions, tidal heating, seismic noise, etc) appear sufficiently small for asteroid diameters > 1 km

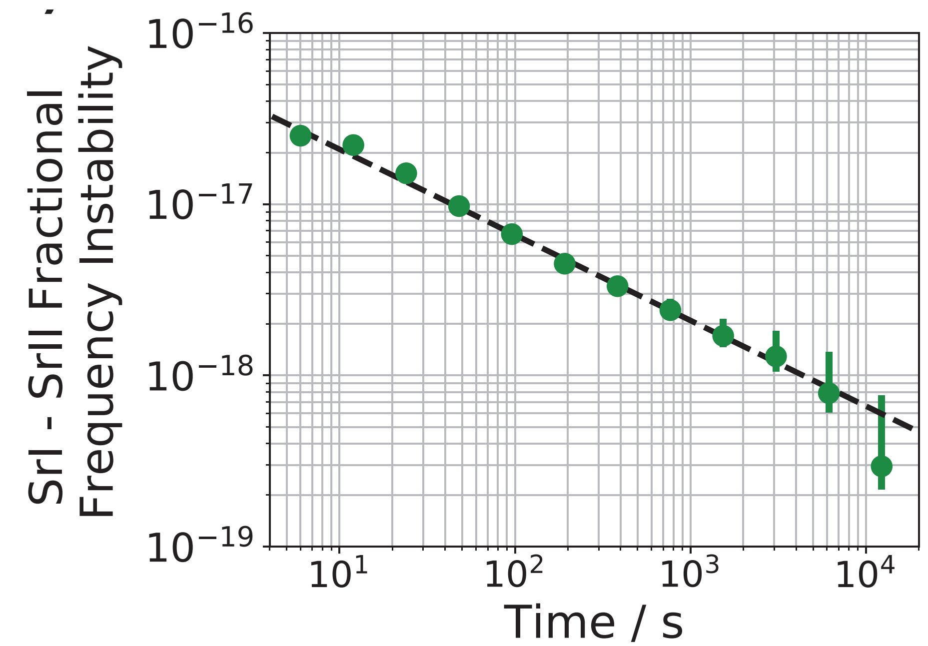
asteroid as inertial proof mass allows significant improvement at low frequencies

Clock Noise

Asteroid is good inertial proof mass, quickly estimate other noise sources



translated current atomic clock



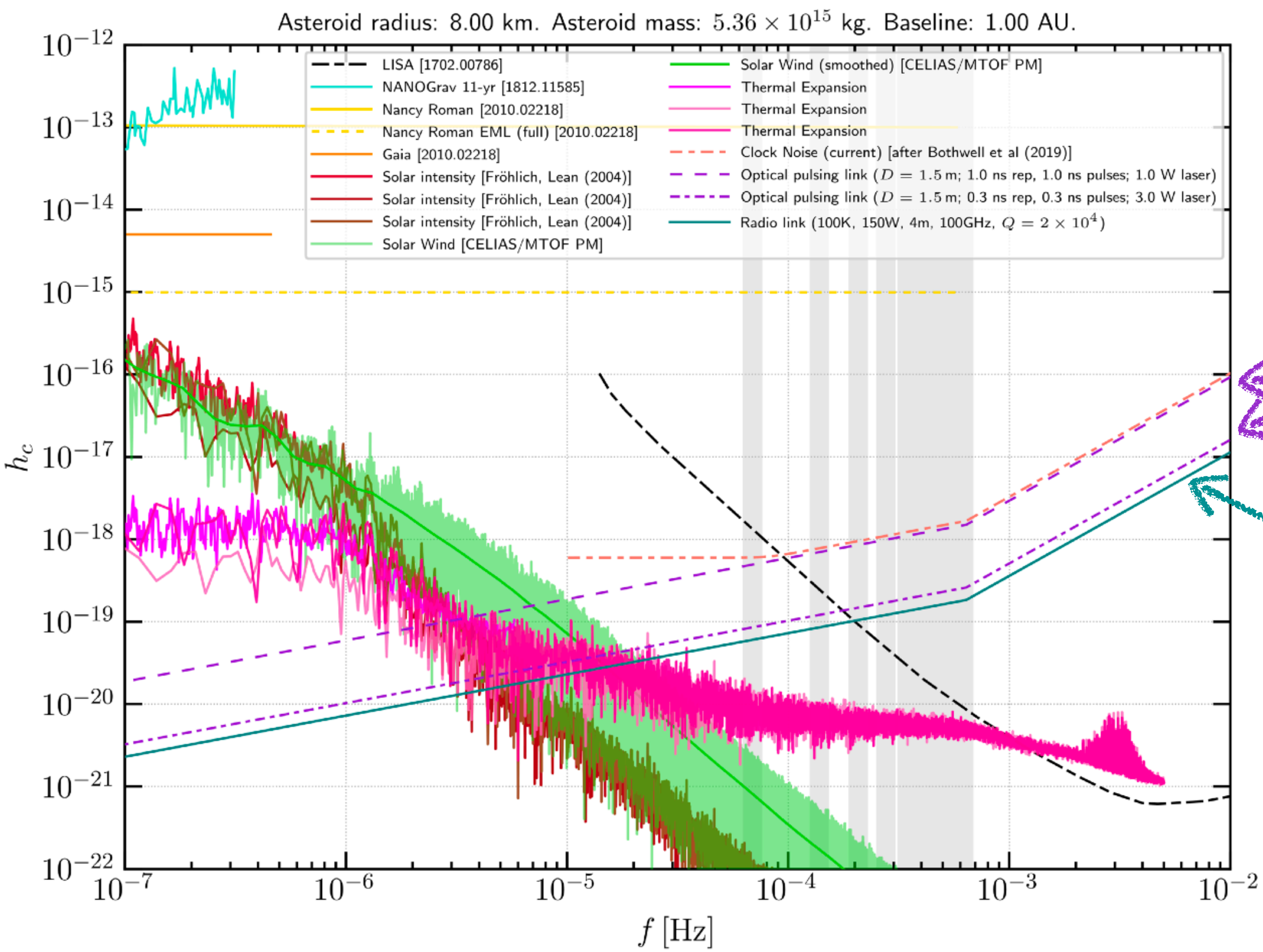
Bothwell et. al. (2019)

existing (terrestrial) clocks already sufficient for great GW sensitivity!

will assume this can be improved sufficiently that it is not limiting

Radio/Optical Link Noise

Estimate radar-ranging accuracy



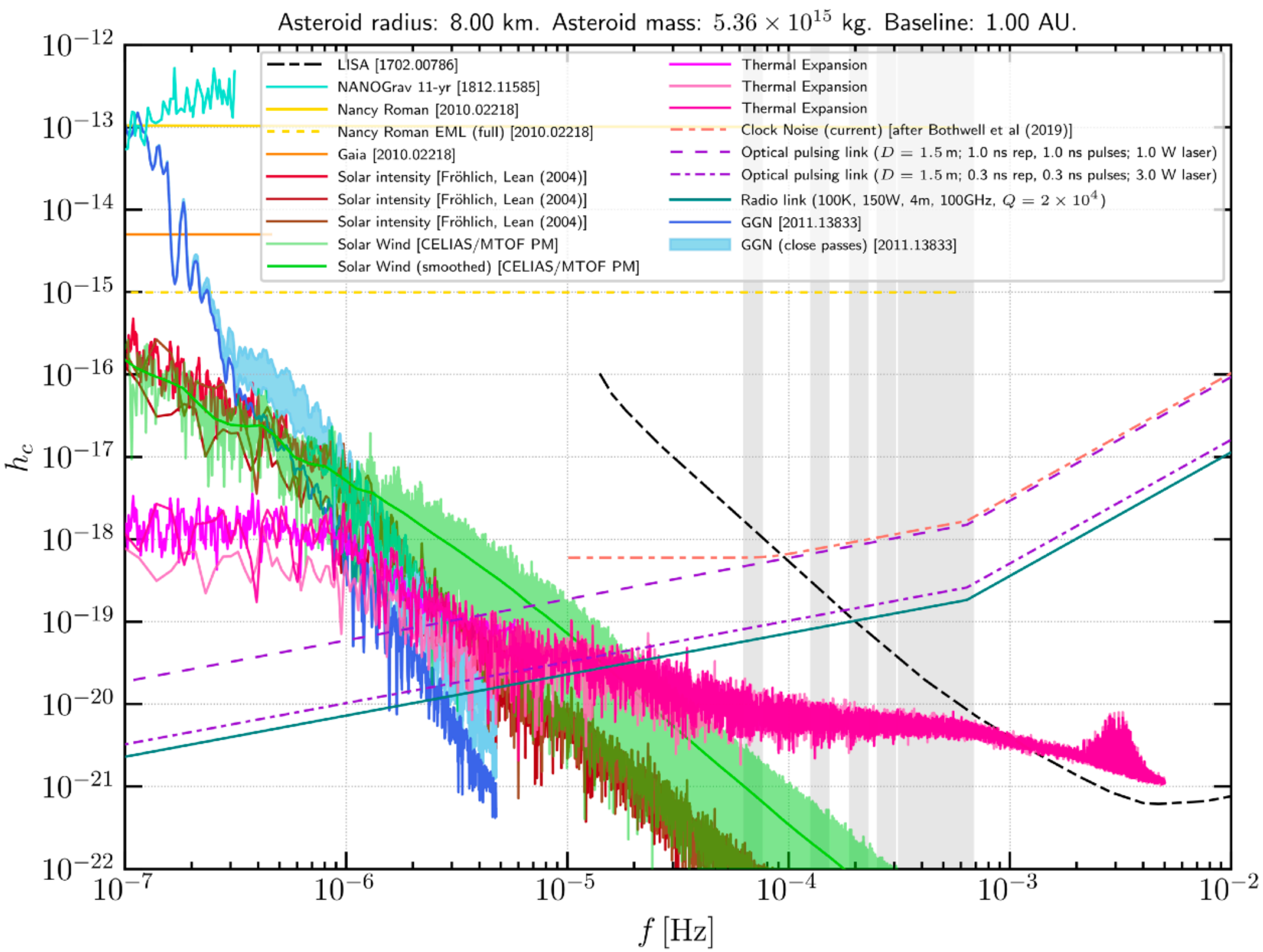
asteroids have significant, uncontrollable relative motion

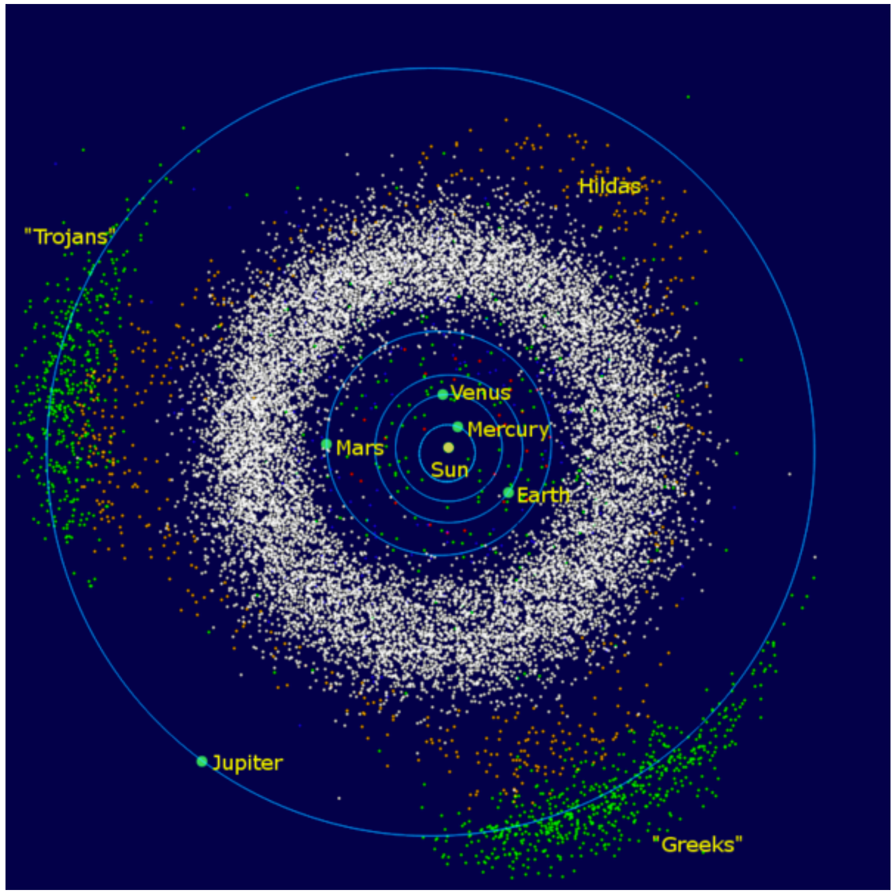
possibly allows a link system with significantly reduced technical complications relative to optical interferometry

Asteroid Gravity Gradient Noise

predominantly around orbital period (of detector) ~ few years

Fedderke, PWG, Rajendran, **PRD** (2021)



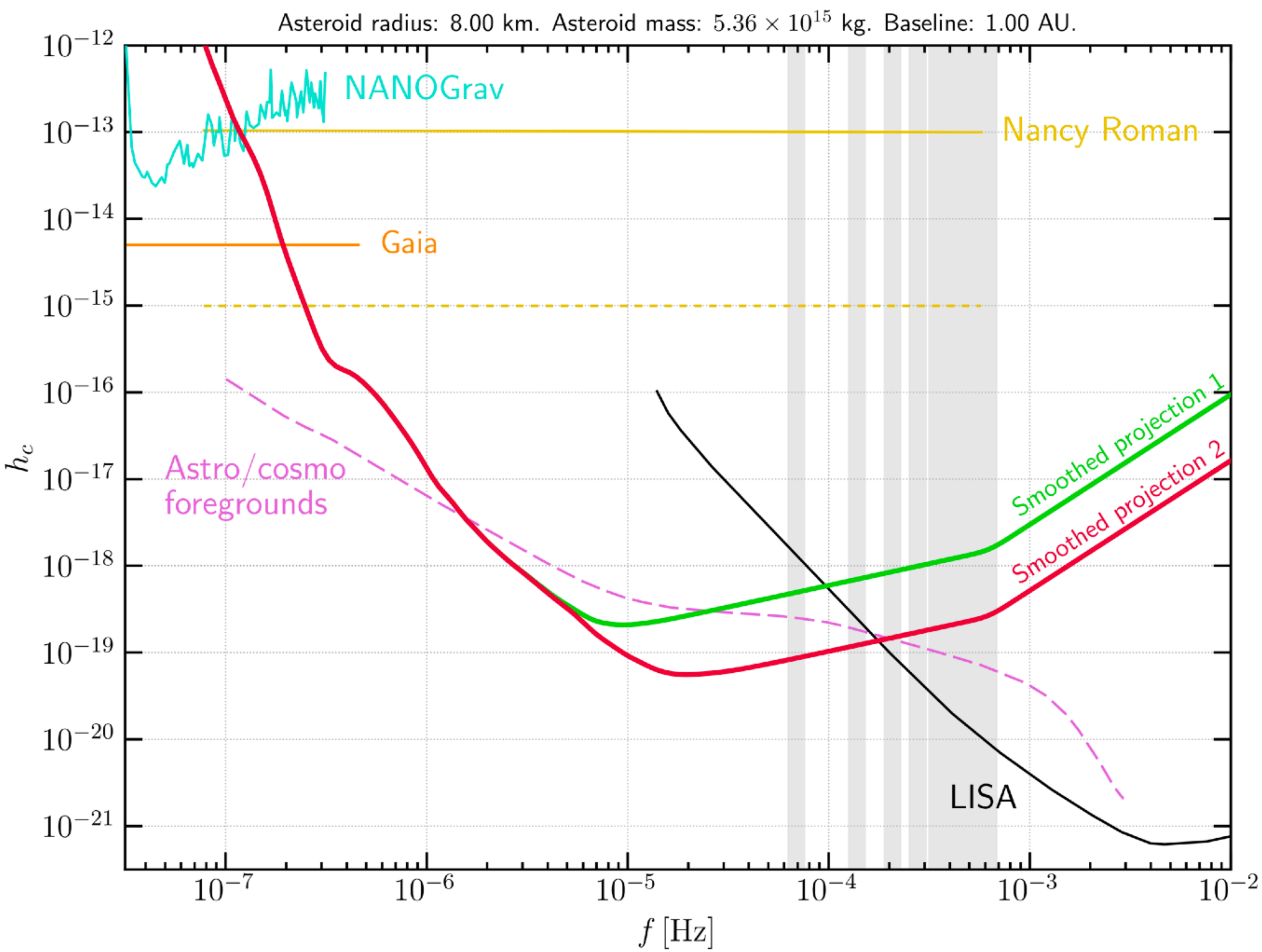


dedicated simulation using NASA JPL asteroid catalog, supplemented with estimate for higher frequency "close pass" noise of unmodeled asteroids using e.g. lunar crater data

cuts off any inner solar system experiment for GW's at frequencies < few x 10^{-7} Hz

Full Sensitivity Curve

"just" placing atomic clock and laser (or radio) link on two asteroids will have sensitivity:



motivates trials of space-qualified atomic clocks

e.g. see talks by M. Safronova, D. Hume, J. Ye, J. Hogan…

also motivates asteroid tests including seismic measurements (mars and moon measurements encouraging)

Asteroids as proof masses with atomic clocks appear capable of observing ~10^{-6} Hz - 10^{-4} Hz band

hopefully encourages further study!

Millicharged Particles and Trapped Ions

(PRELIMINARY)

with

Dmitry Budker

Harikrishnan Ramani

Ferdinand Schmidt-Kaler

Christian Smorra

Stefan Ulmer

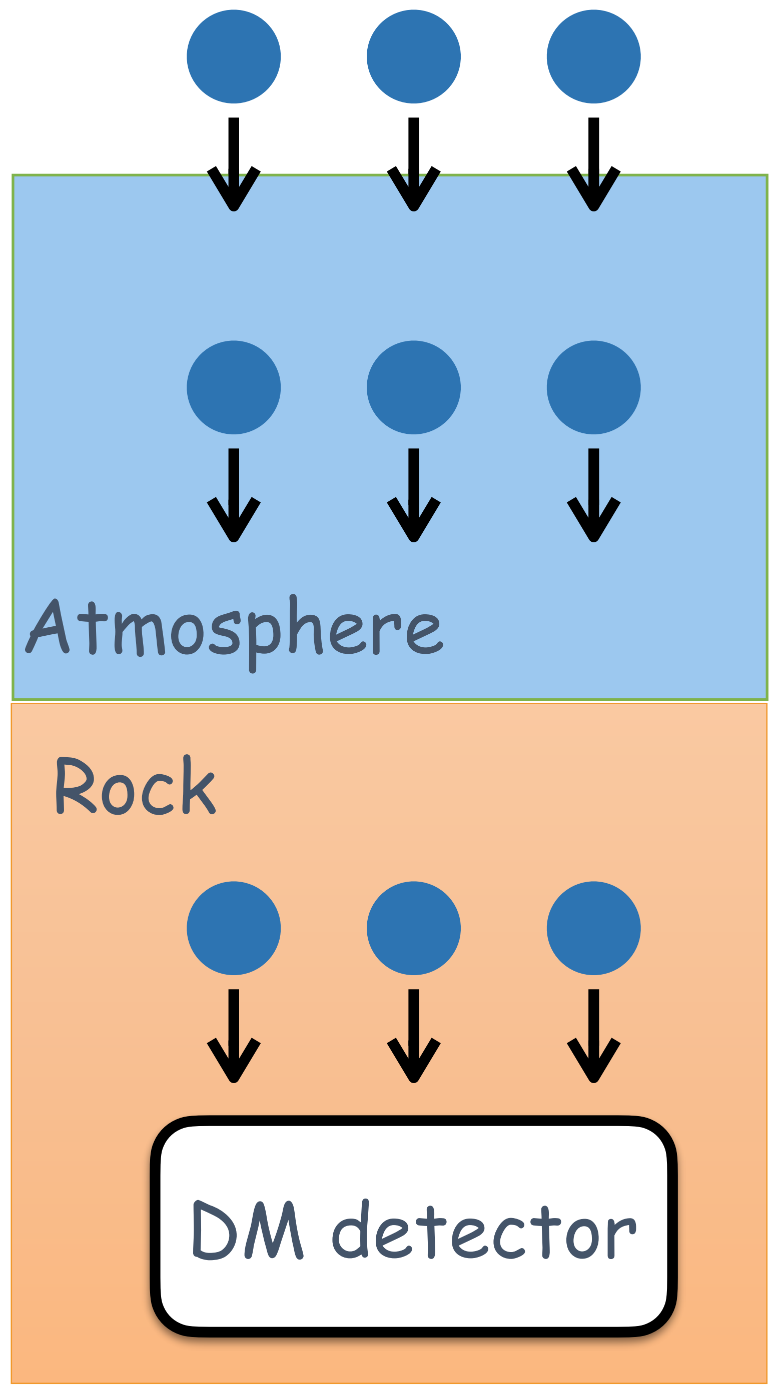
to appear

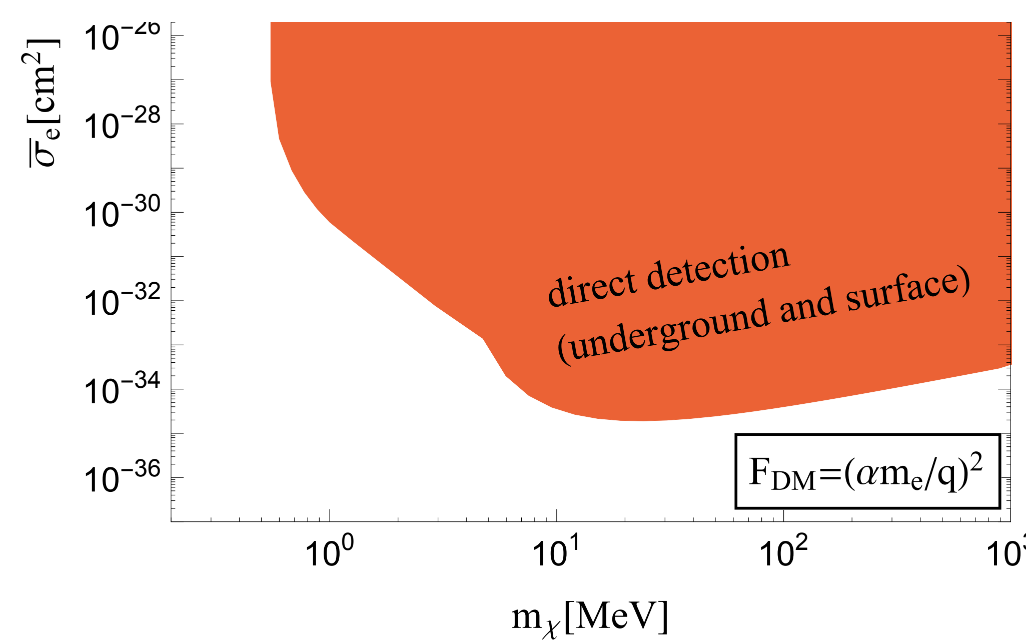
Detection of Millicharged Particles

significant interest recently in "millicharged" particles (charge = εe)

- mystery of charge quantization, dark matter candidate, EDGES anomaly…

weakly coupled particles penetrate Earth





1905.06348 Emken et al

Detection of Millicharged Particles

significant interest recently in "millicharged" particles (charge = εe)

- mystery of charge quantization, dark matter candidate, EDGES anomaly…

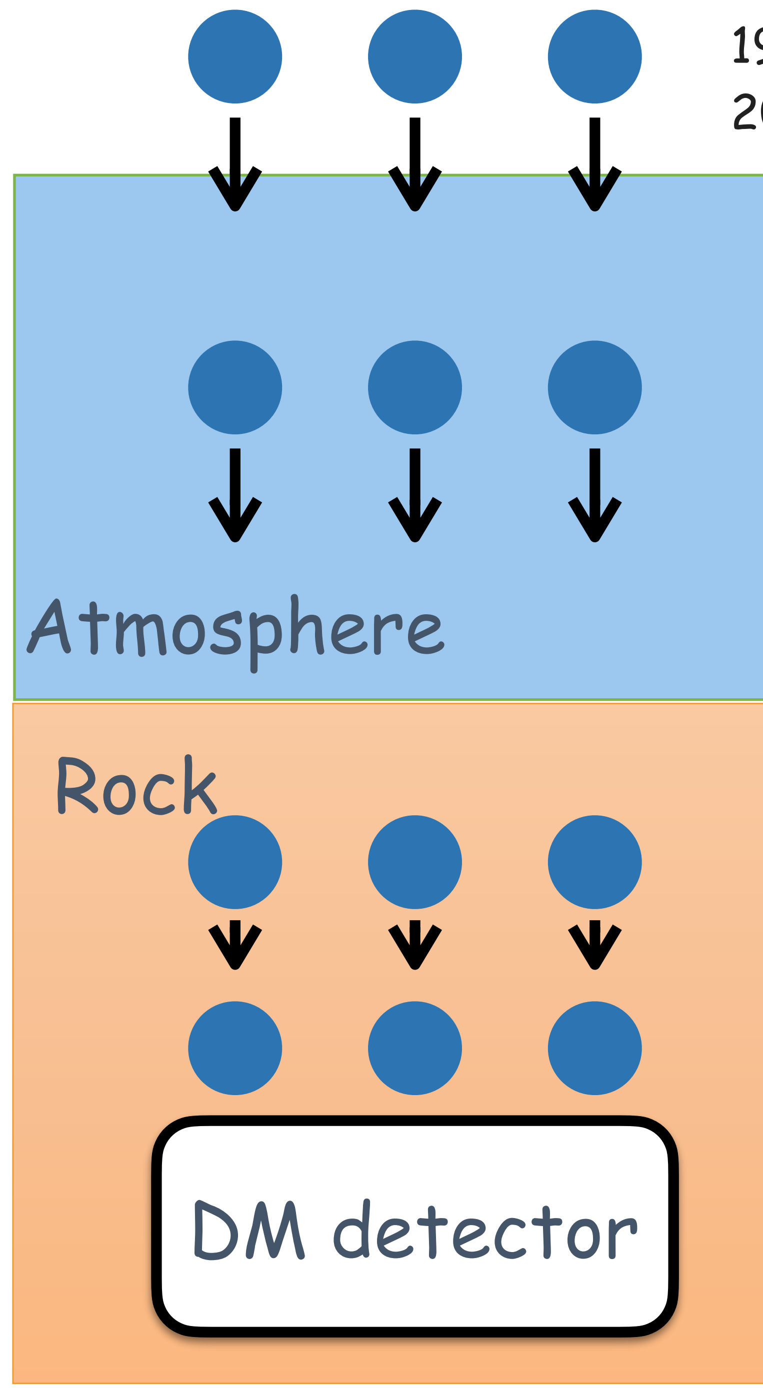
1907.00011 M. Pospelov, S. Rajendran, H. Ramani
2012.03957 M.Pospelov & H. Ramani

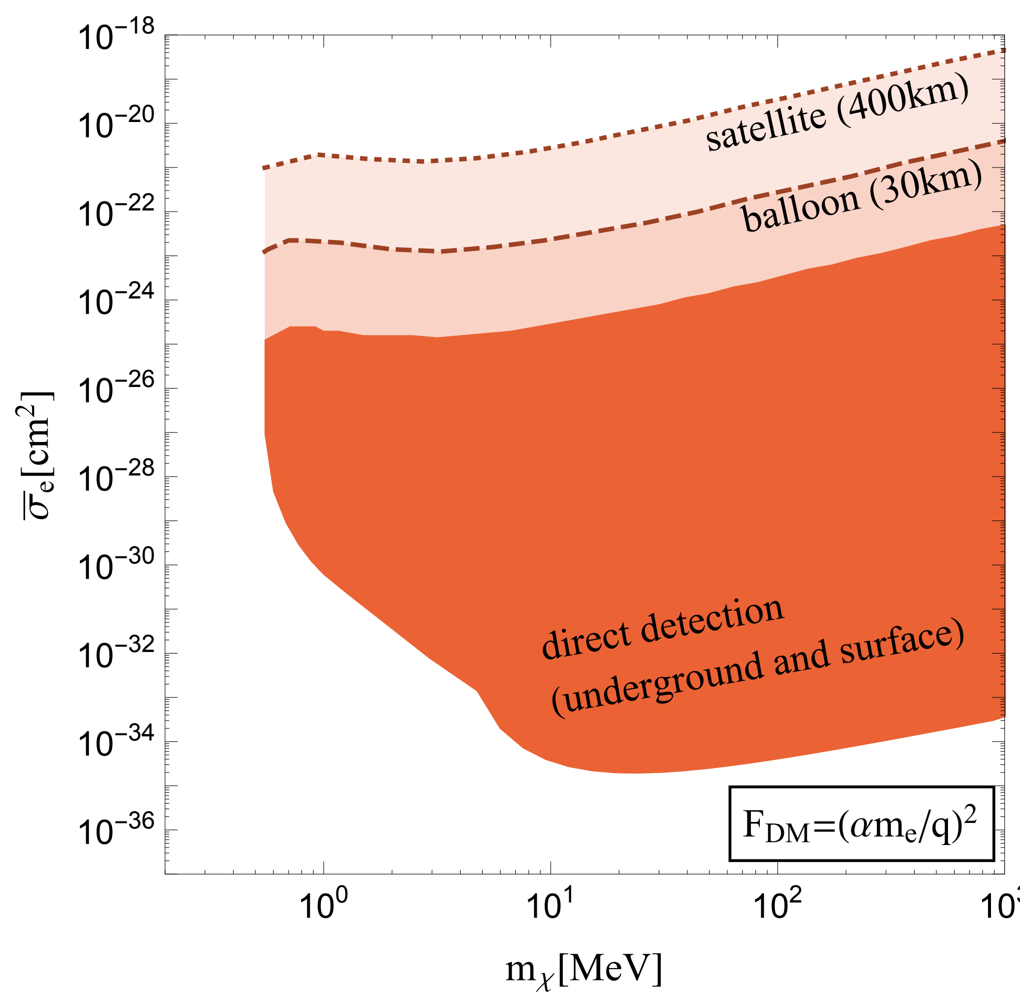
millicharged particles can have large couplings

can get stuck + thermalize to 300 K ~ 25 meV

most direct detection expts have thresholds ~ keV maybe down to ~ eV

still diffuse downwards "traffic jam" ➜ very large number densities!





1905.06348 Emken et al

how can we detect a large abundance of low energy particles?

Ion Traps as Detectors

Ion traps excellent at isolation, can detect very low energy depositions!

Similar goals to quantum computing

Ambient millicharged particles scatter off trapped ion, heating it

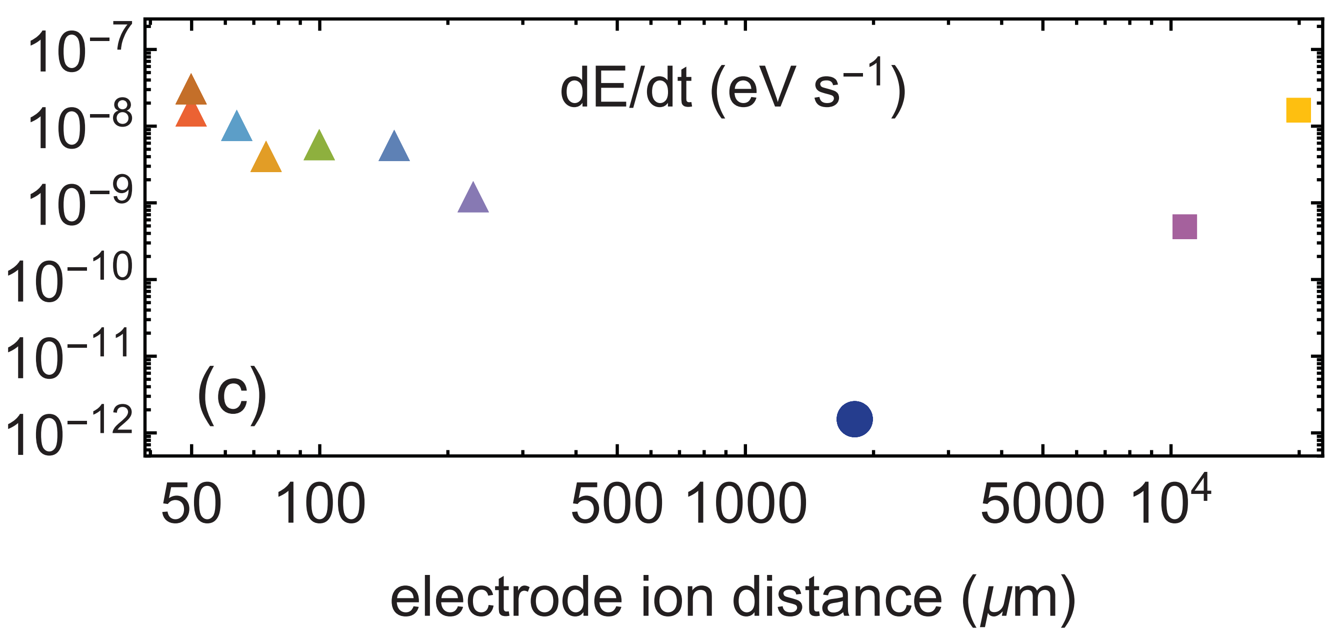
BASE experiment, CERN

Measurement of Ultralow Heating Rates of a Single Antiproton in a Cryogenic Penning Trap

M. J. Borchert,[1,2,*] P. E. Blessing,[1,3] J. A. Devlin,[1] J. A. Harrington,[1,4] T. Higuchi,[1,5] J. Morgner,[1,2] C. Smorra,[1] E. Wursten,[1,7] M. Bohman,[1,4] M. Wiesinger,[1,4] A. Mooser,[1] K. Blaum,[4] Y. Matsuda,[5] C. Ospelkaus,[2,8] W. Quint,[3,9] J. Walz,[6,10] Y. Yamazaki,[11] and S. Ulmer[1]

sensitive to collisions depositing ~ neV

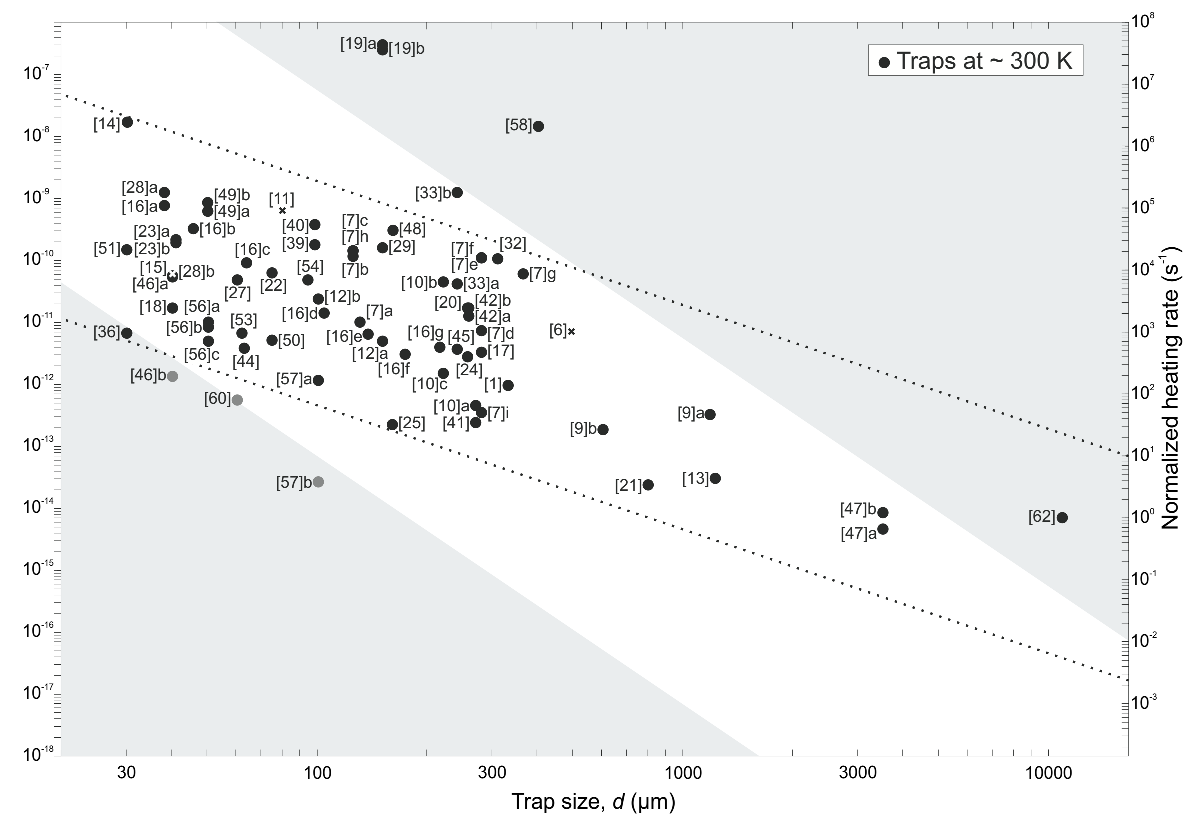
in overall heating rate



Ion Traps

e.g. ^{40}Ca ions sensitive to ~ $10^{-9}\,\frac{\text{eV}}{\text{sec}}$

with individual collisions ~ few neV

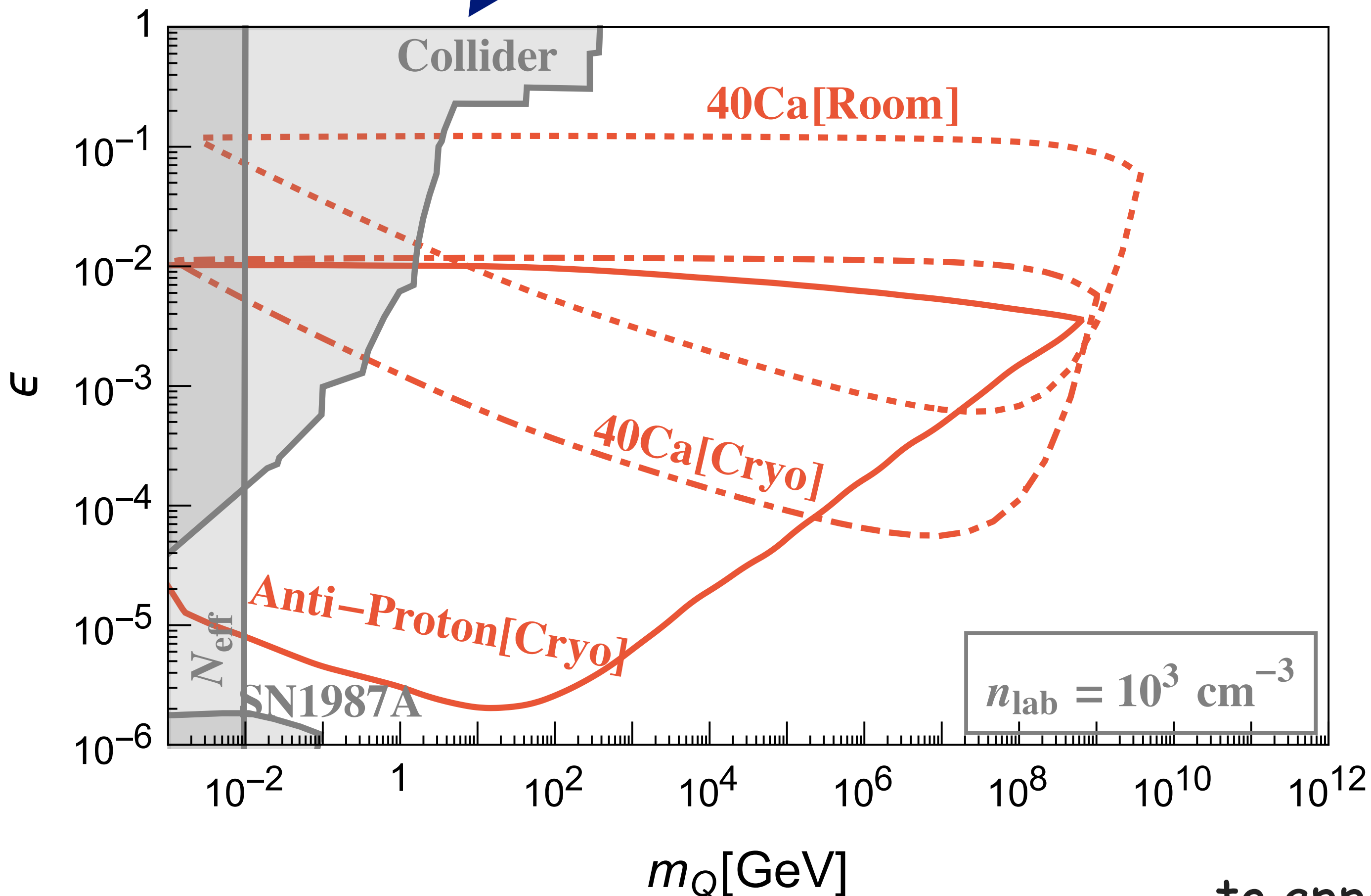


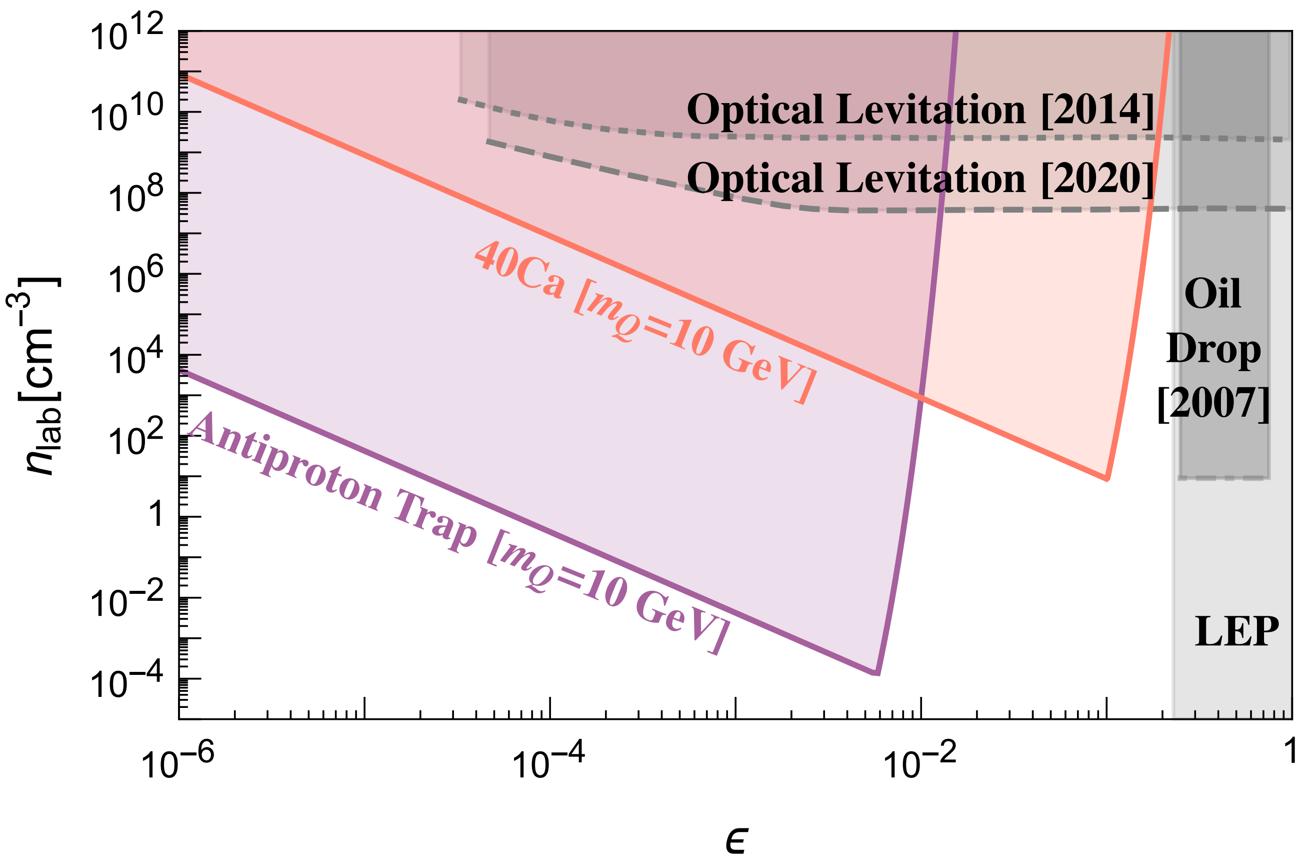
1409.6572 M. Brownnutt, M. Kumph, P. Rabl & R. Blatt

Ion Traps as Detectors

if millicharged particles exist, existing ion traps already reach well past previous bounds

e.g. talk by J. Boyd





to appear

significant improvements possible (e.g. highly charged ions, single events, ion crystals…)

Conclusions

1. Asteroids are good inertial proof masses, may allow atomic clocks to detect GW's in challenging ~ 10^{-6} Hz - 10^{-4} Hz band

2. Trapped ions are excellent detectors for millicharged particles with large cross sections. Already set new limits, large improvements possible.