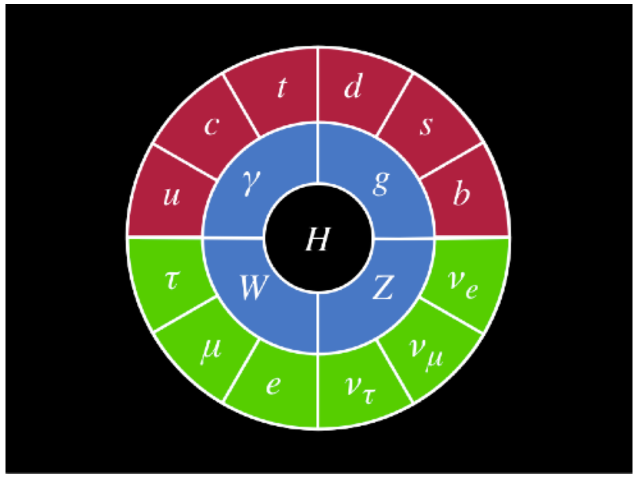
Quantum Sensing for Dark Matter and Gravitational Waves

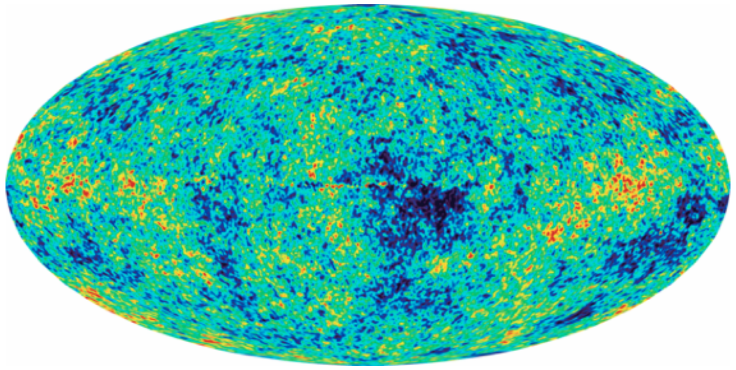
Peter Graham

Stanford

Open Questions

The Standard Model of Particle Physics and Cosmology
is remarkably successful





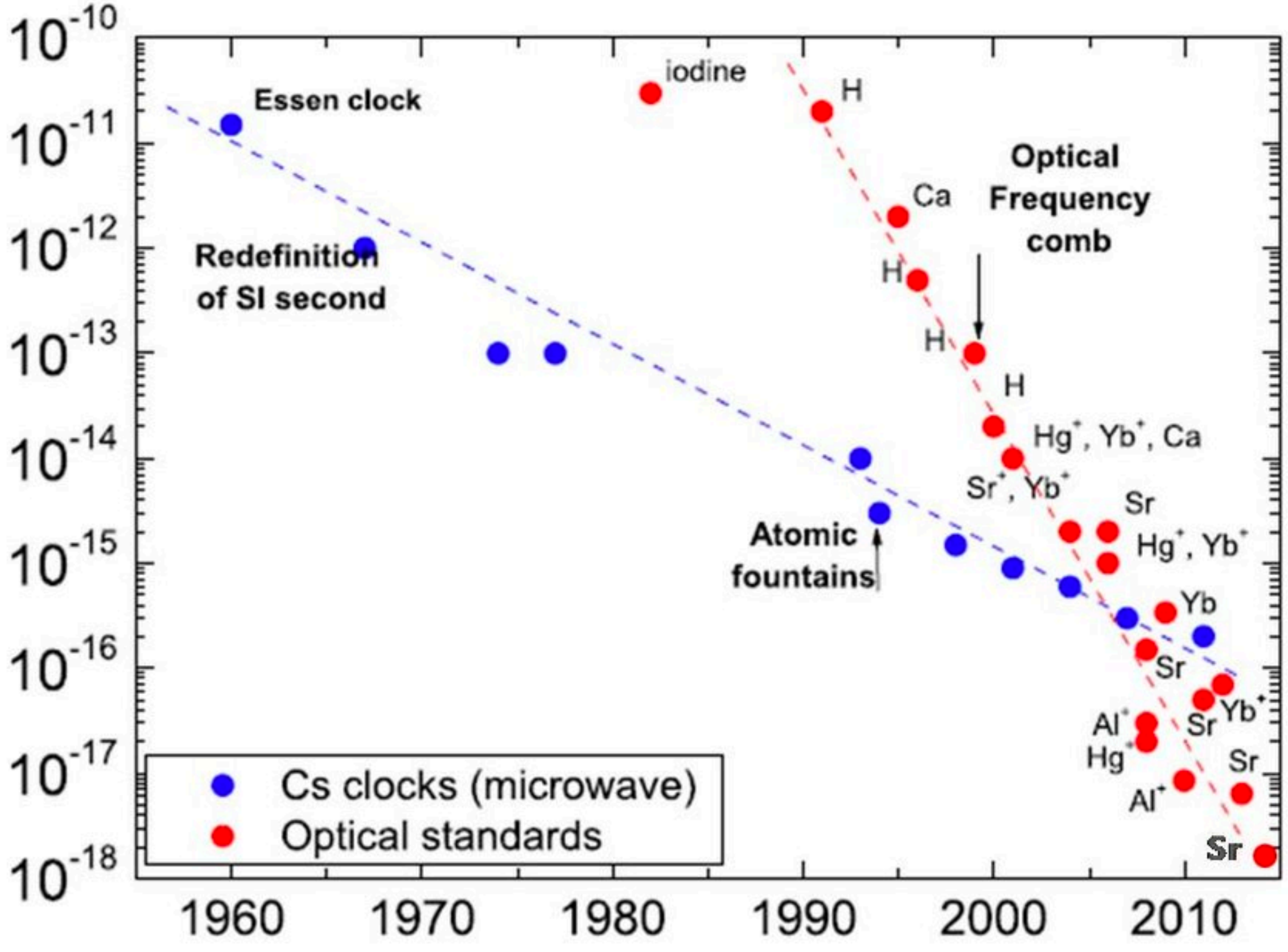
but this success deepens the remaining mysteries

e.g. we'd like to understand the nature of dark matter and
dark energy and the earliest moments of our universe

Quantum Technologies?

Quantum sensors achieved incredible sensitivities!

e.g. atomic clocks have improved **rapidly**



complementary to more traditional particle colliders/detectors

theorist/experimentalist collaboration led to many new directions

likely many more still undiscovered!

Examples of Quantum Technologies for Fundamental Physics

I can't overview entire field, will choose a few examples I can discuss:

1. Millicharged Particles and Trapped Ions (in progress)

2. Atomic Interferometry for Gravitational Waves ~ Hz

3. Atomic Clocks and Gravitational Waves at ~ μHz (in progress)

Of course community is pursuing MANY more,
I'm excited to hear all the talks!

Millicharged Particle Detection with Trapped Ions

with

Dmitry Budker

Harikrishnan Ramani

Ferdinand Schmidt-Kaler

Christian Smorra

Stefan Ulmer

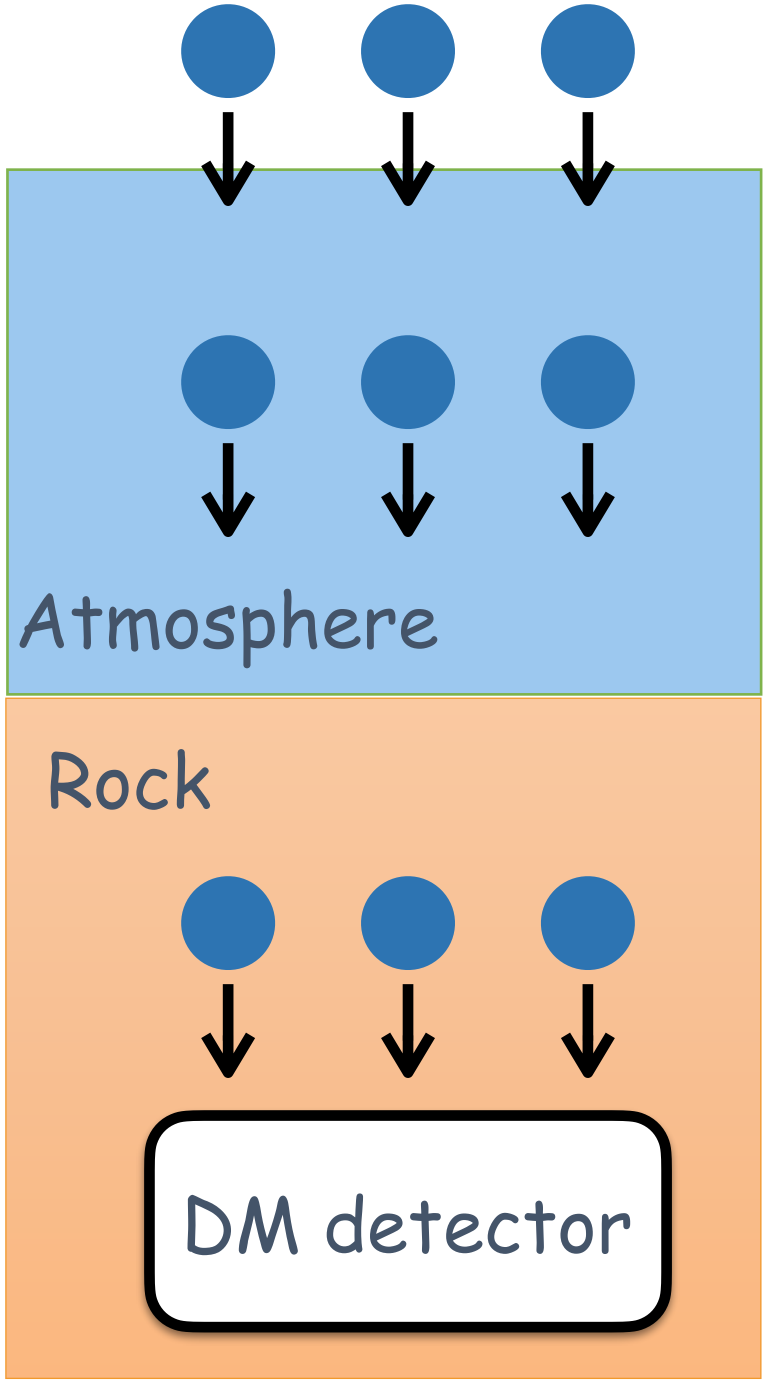
to appear

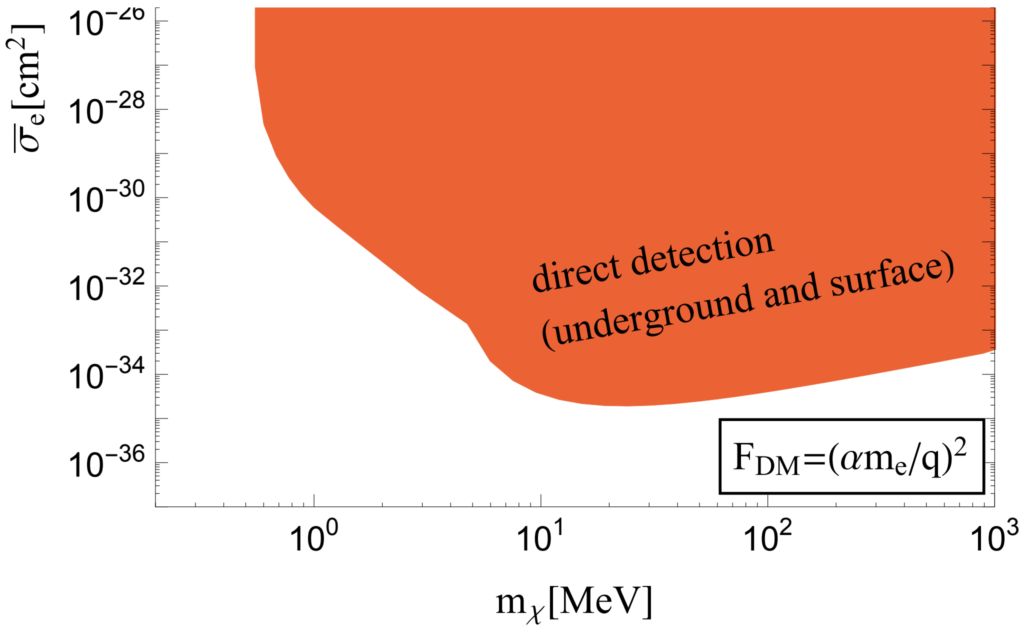
Detection of Millicharged Particles

significant interest recently in “millicharged” particles (charge = εe)

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

generally weakly coupled particles penetrate Earth





1905.06348 Emken et al

Detection of Millicharged Particles

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

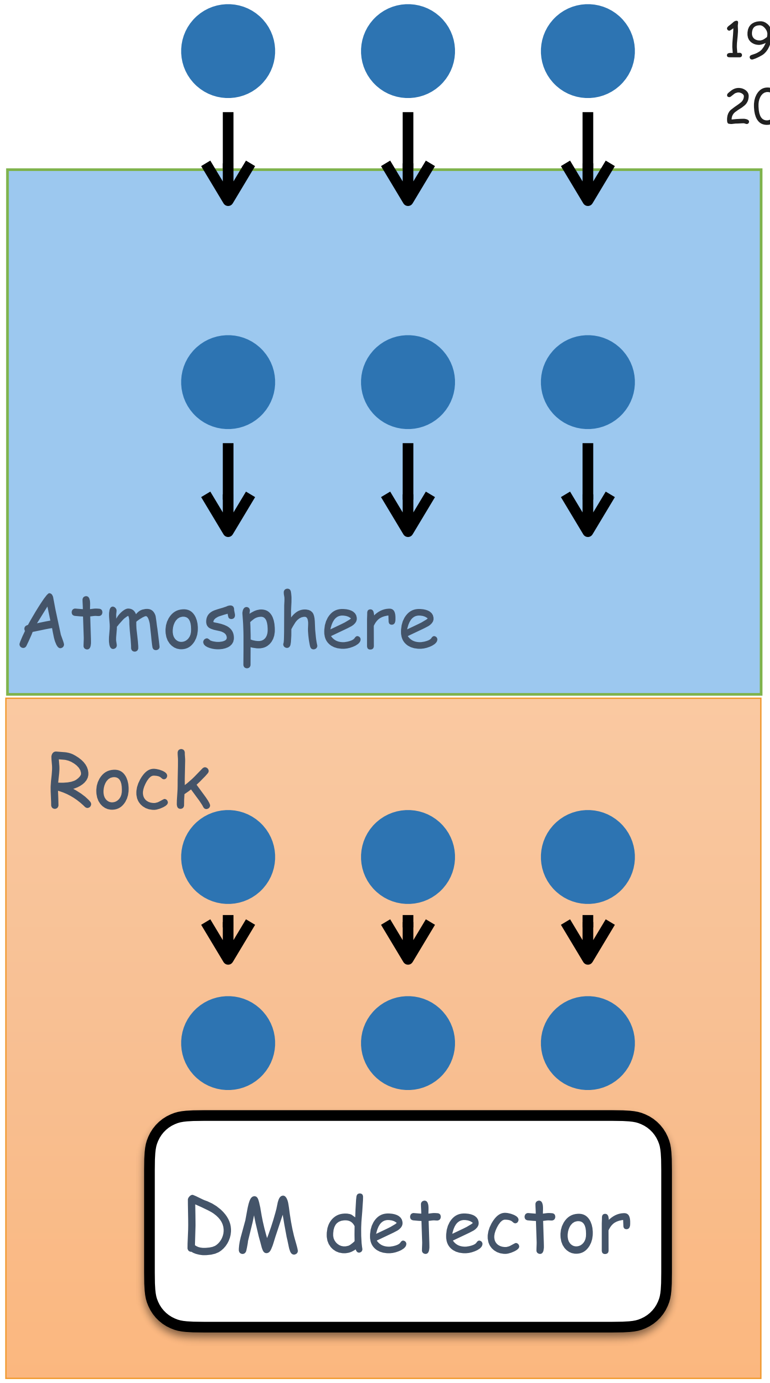
- mystery of charge quantization, dark matter candidate, EDGES anomaly…

millicharged particles can
have large couplings

can get stopped + 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!

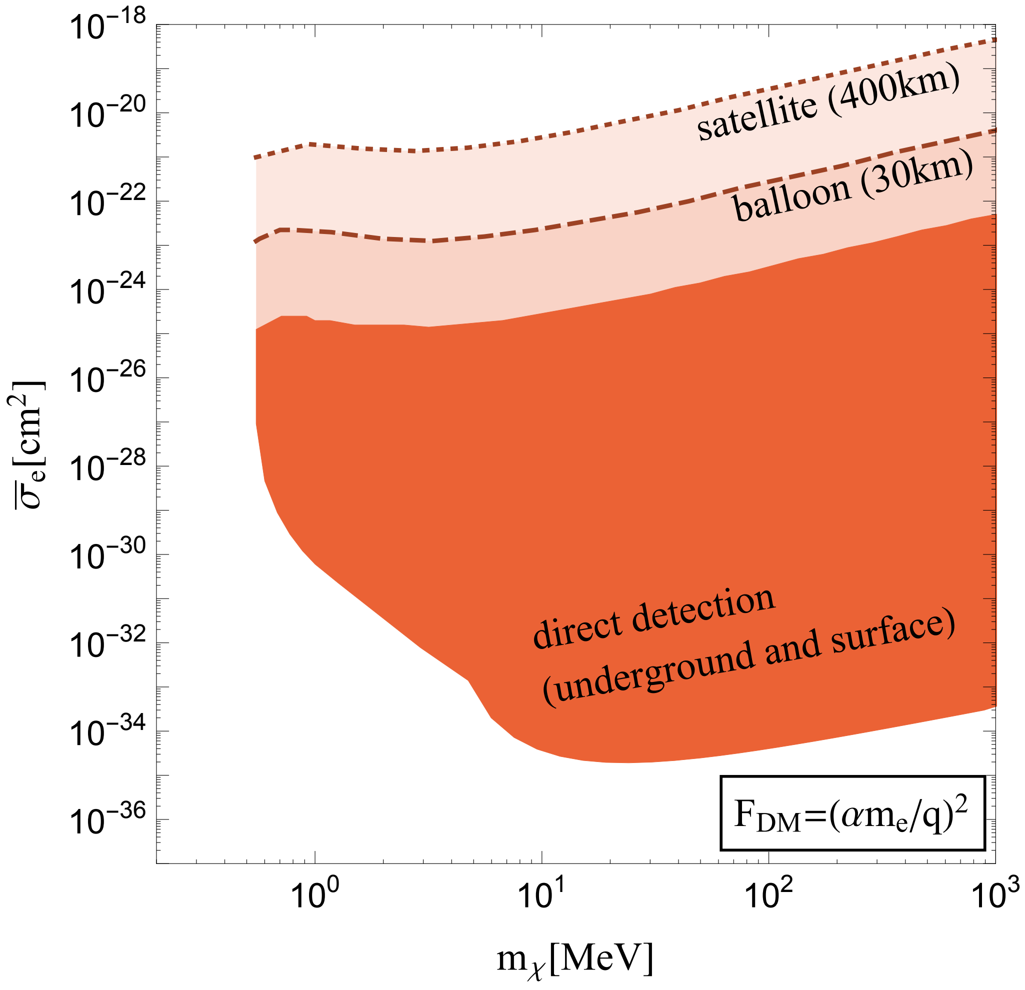


Atmosphere

Rock

DM detector

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



1905.06348 Emken et al

A New Kind of Dark Matter Detector

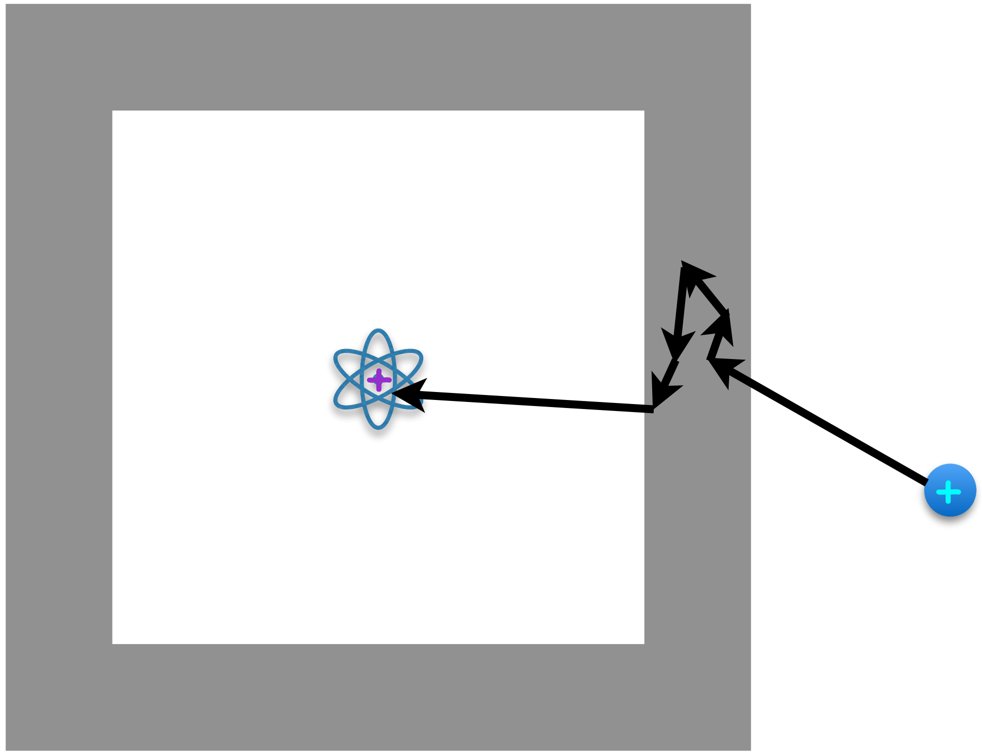
So have low energy millicharged particles, but with large density and large cross section!

How can we detect this?

Need a sensitive low threshold detector
Low target mass acceptable
Maximize charged particle scattering

➜ Trapped ion

Ambient millicharged particles scatter off trapped ion, heating it



$$\dot{H} = \sqrt{\frac{2}{\pi}} \frac{n_{\rm mcp} m_{\rm mcp} m_{\rm ion} (T_{\rm mcp} - T_{\rm ion})}{(m_{\rm ion} + m_{\rm mcp})^2} \frac{\sigma_0}{u_{\rm th}^3}$$

$$u_{\rm th}^2 = \frac{T_{\rm ion}}{m_{\rm ion}} + \frac{T_{\rm mcp}}{m_{\rm mcp}}$$

only the ion needs to be cooled

if whole trap is cryogenic the millicharges cool in walls
➜ enhances number density inside trap

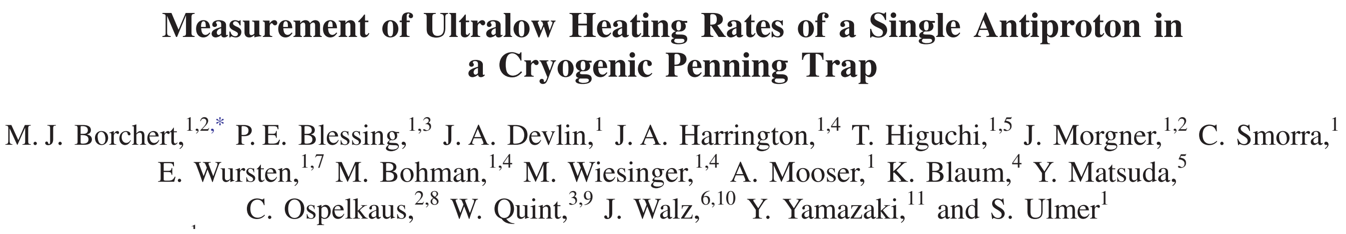
long-range Coulomb scattering ➜ larger cross section at lower velocities

Ion Traps as Detectors

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

Much recent progress motivated by quantum computing

BASE experiment, CERN

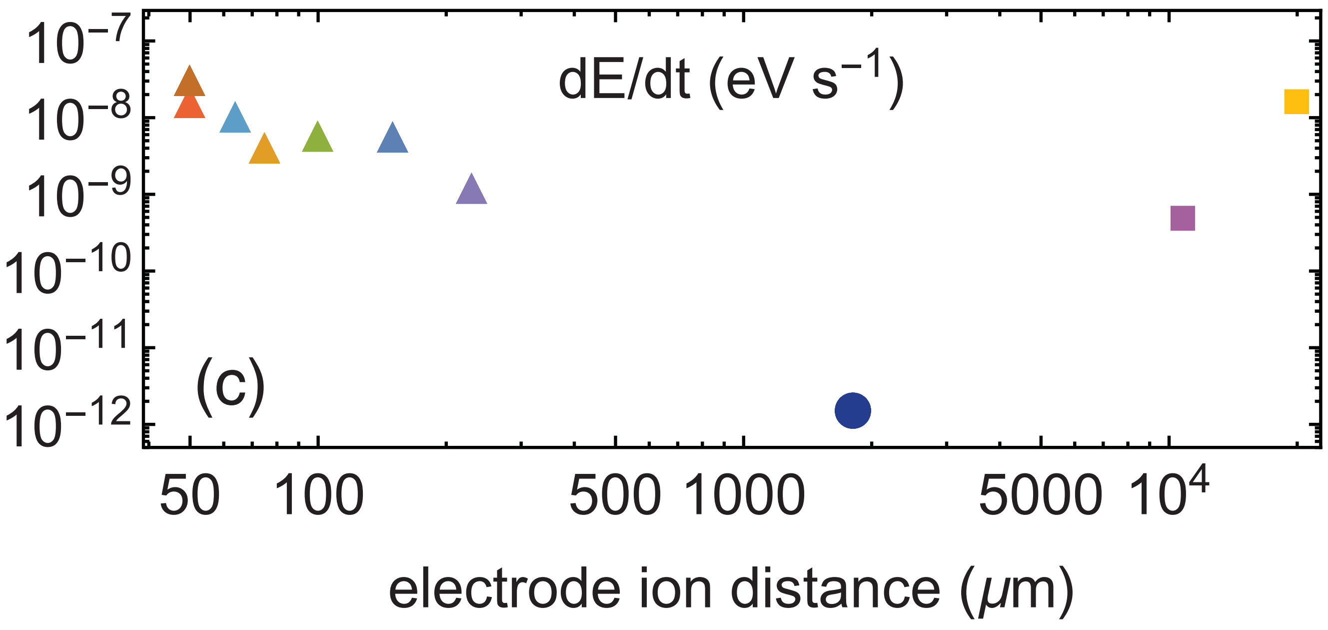


Measurement of Ultralow Heating Rates of a Single Antiproton in a Cryogenic Penning Trap

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

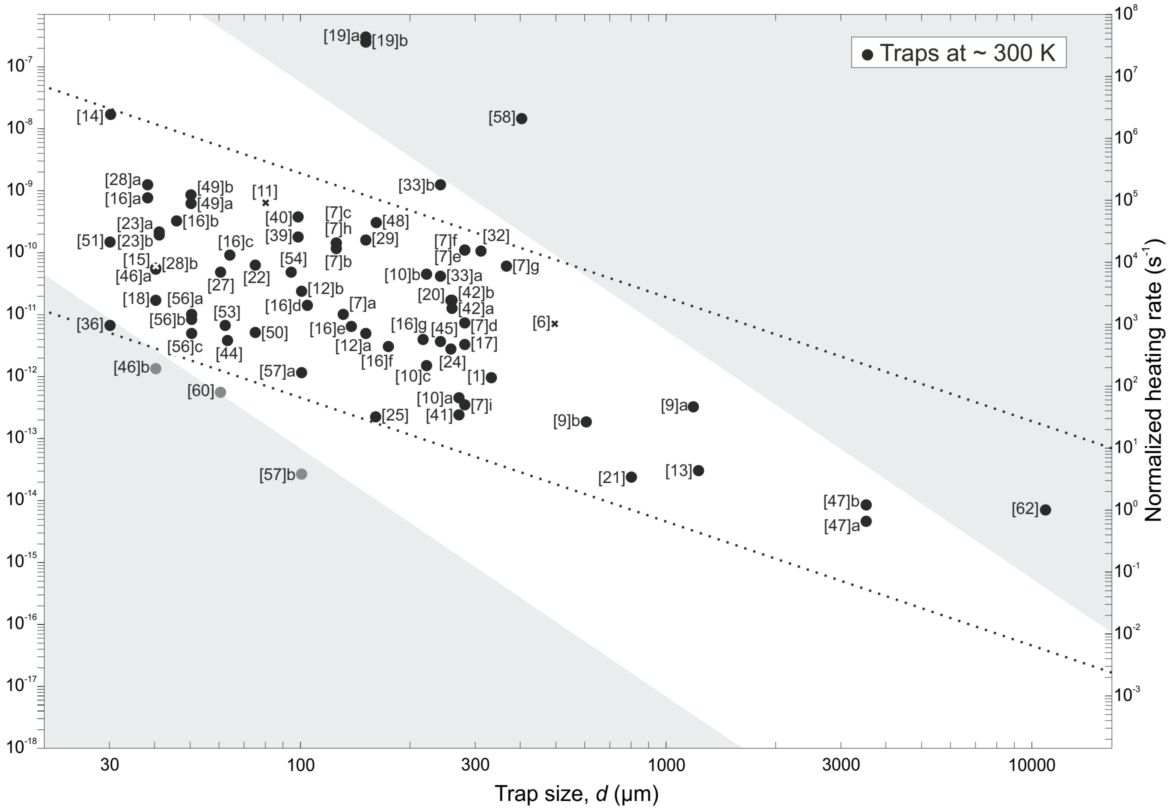
in overall heating rate



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

New Limits From Ion Traps

We choose 3 experiments to set new limits

but many more ion trap experiments have achieved low noise and could extend reach

Experiment	Type	Ion	V_z	T_{wall}	ω_p [neV]	T_{trap}[neV]	Heat Rate(neV/sec)
Hite et al, 2012[3]	Paul	^{9}Be	0.1 V	300 K	$\omega_z = 14.8$	14.8	640
Goodwin et al, 2016 [4]	Penning	^{40}Ca	175 V	300 K	$\omega_z = 1.24$	1.24	0.37
Borchert et al, 2019 [5]	Penning	p^-	0.6 V	5.6 K	$\omega_+ = 73.8$	7380	0.002
					$\omega_- = 0.041$		

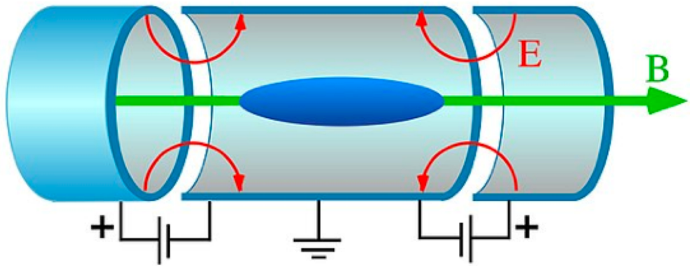
BASE → Borchert et al, 2019 [5]

room temp, cryogenic

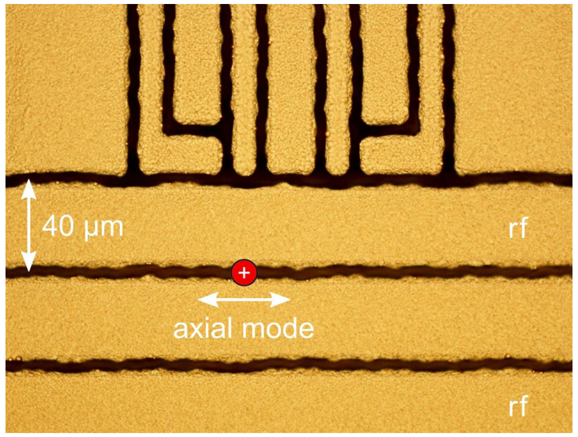
detector threshold

cooled ions

sensitivity



Penning Trap



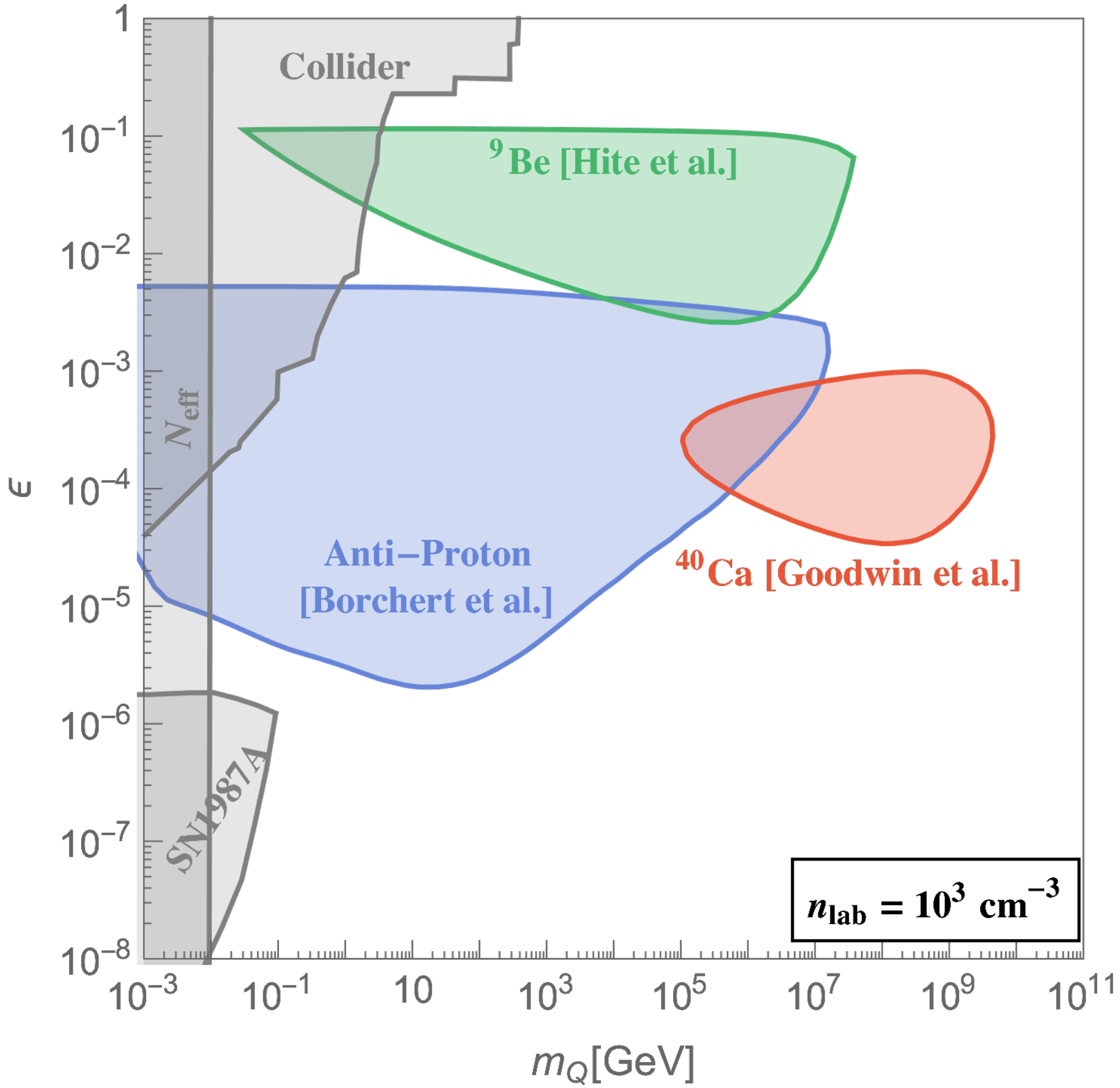
Paul Trap
(Hite et al)

New Limits From Ion Traps

Different experiments have very complementary reach!

Significant differences between traps

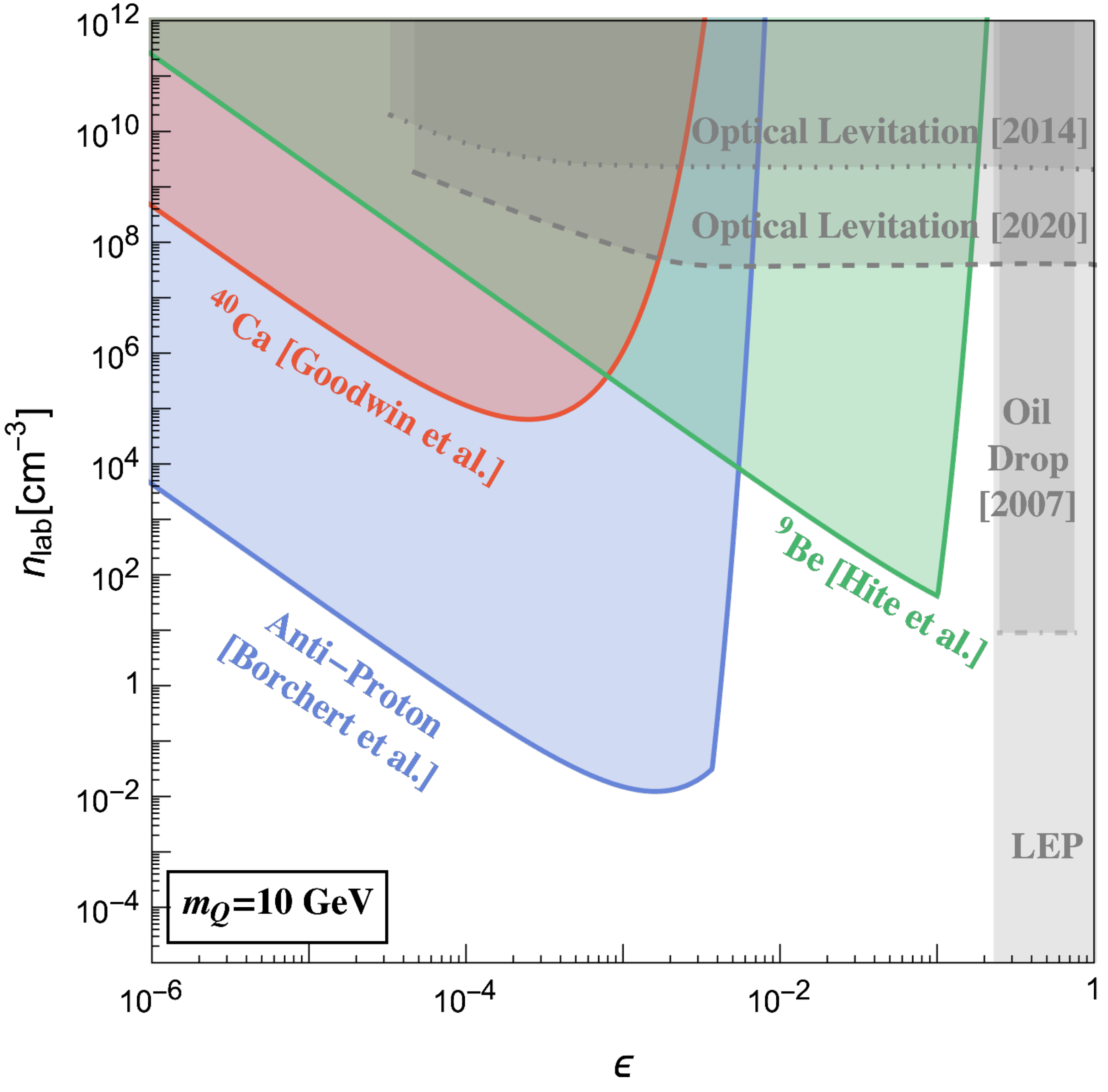
- threshold
- target mass
- heating rate
- temperature



to appear

New Limits From Ion Traps

existing ion traps already reach well past previous bounds



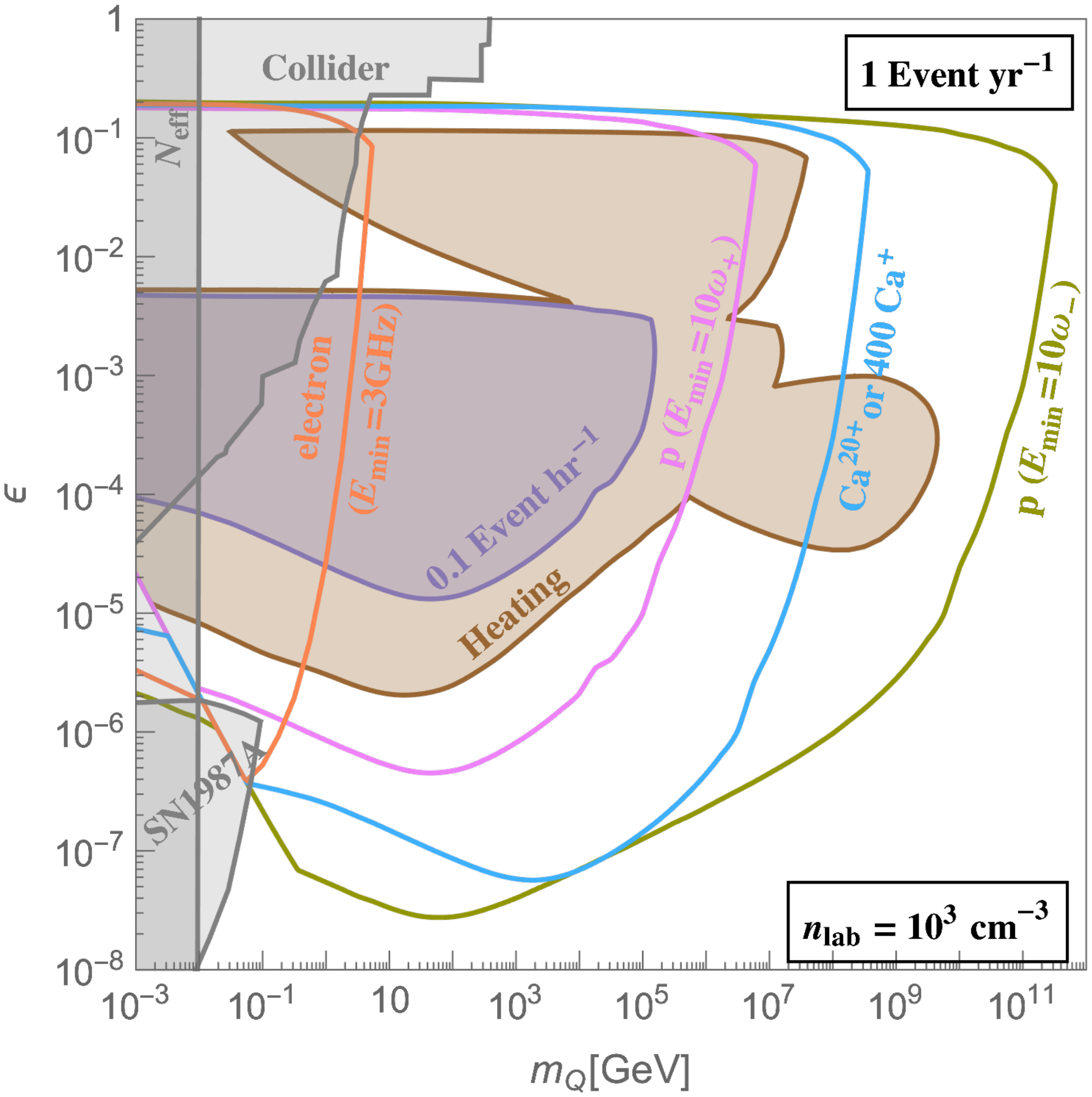
to appear

Future Prospects

past measurements not made for dark matter detection already place strong constraints

significant improvement possible in future with experiments designed to search for millicharges

- observing individual events reduces heating background, requires continuous monitoring of ion (already employed in some experiments)
- highly charged ion boosts signal
- lower threshold boosts event rate
- collective excitations in ion crystals could also reduce backgrounds



to appear

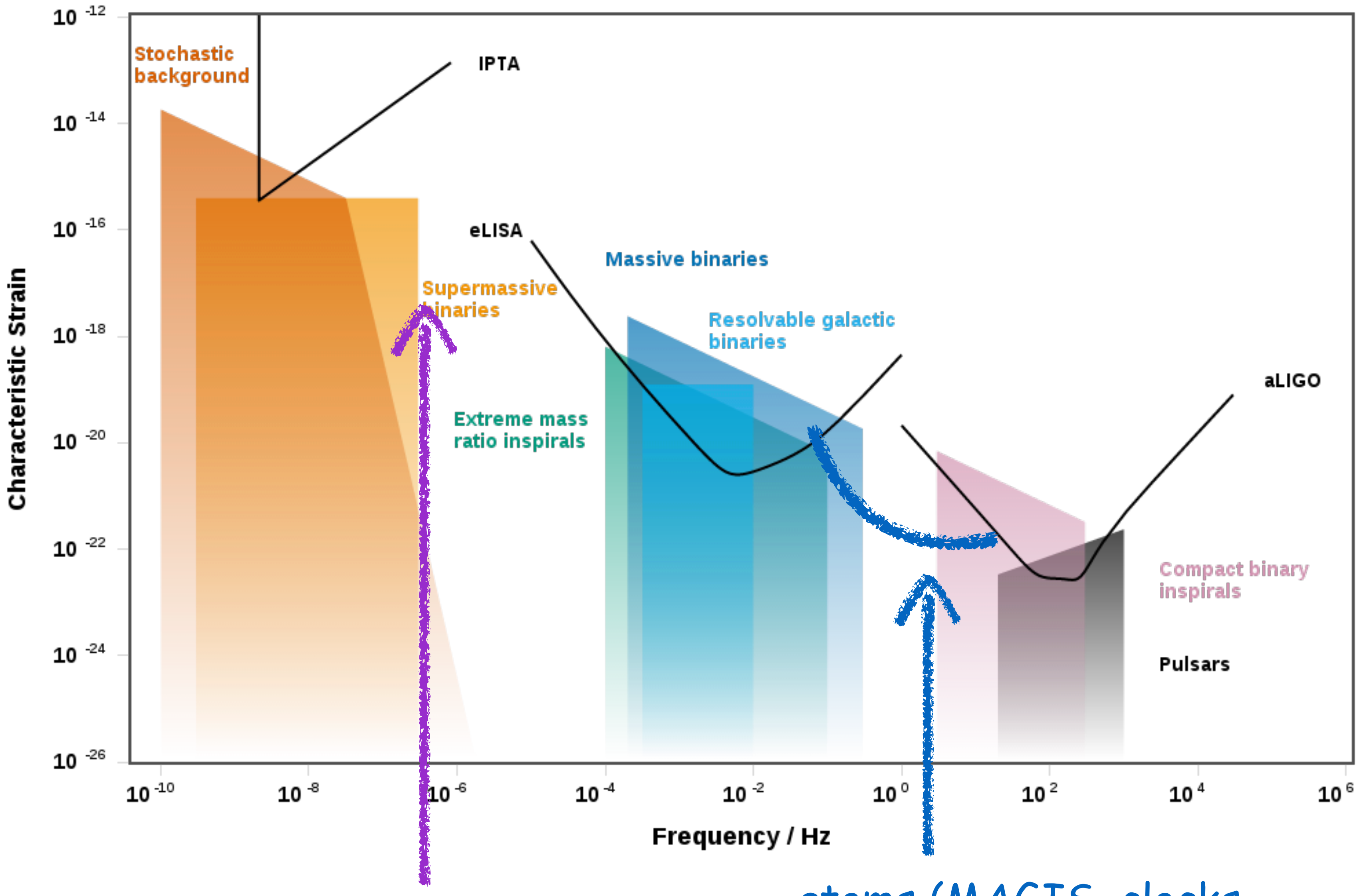
Gravitational Waves

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

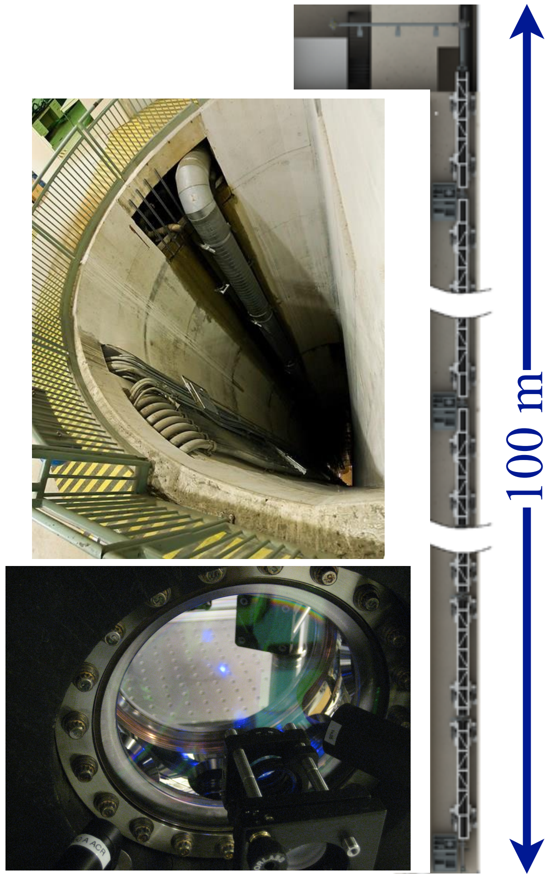
Mid-band (~Hz) Gravitational Waves with Atom Interferometry

International Efforts in Gravitational Wave Detection with Atom Interferometry

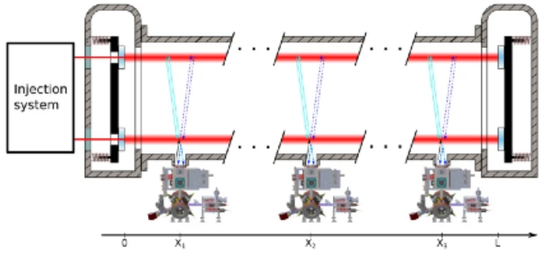
Terrestrial Detectors under construction now:

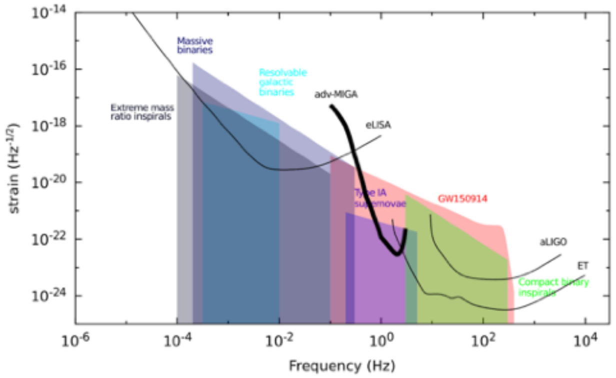
Project	Baseline Length	Number of Baselines	Orientation	Atom	Atom Optics	Location
MAGIS-100	100 m	1	Vertical	Sr	Clock AI, Bragg	USA
AION [10]	100 m	1	Vertical	Sr	Clock AI	UK
MIGA [5]	200 m	2	Horizontal	Rb	Bragg	France
ZAIGA [8]	300 m	3	Vertical	Rb, Sr	Raman, Bragg, OLC	China

MAGIS-100 (Fermilab)

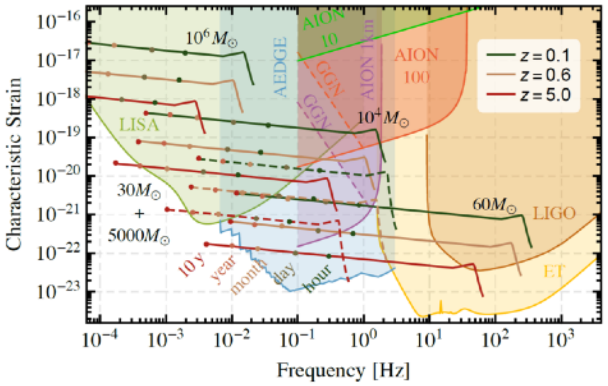


MIGA (France)

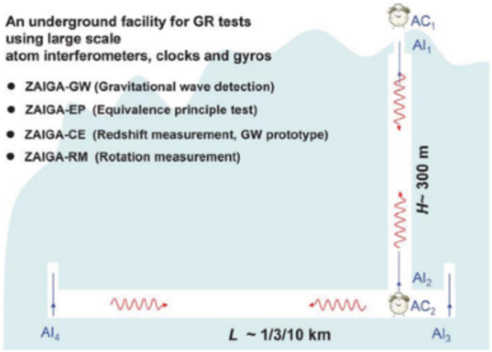


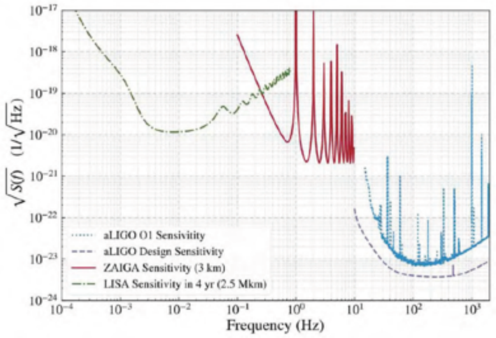


AION (UK)



ZAIGA (China)





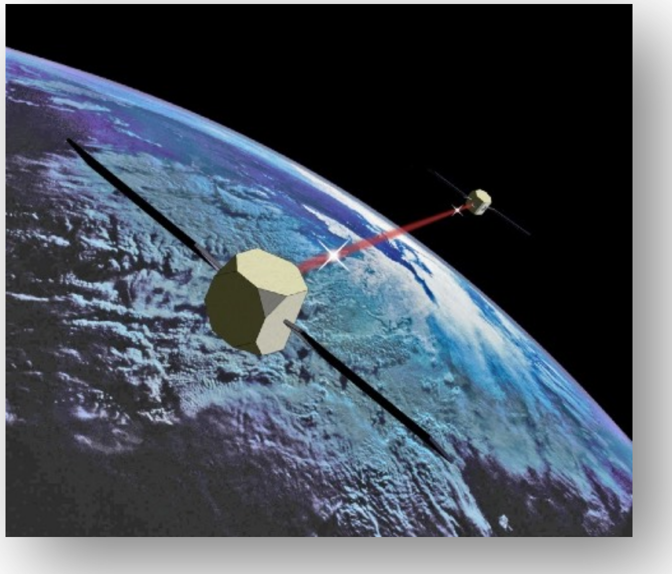
Plans (only) for satellite detectors, e.g. MAGIS and AEDGE

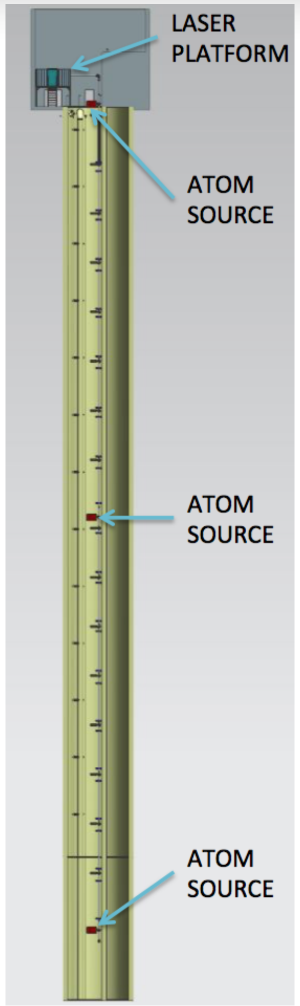
leverage technology developed in these terrestrial detectors

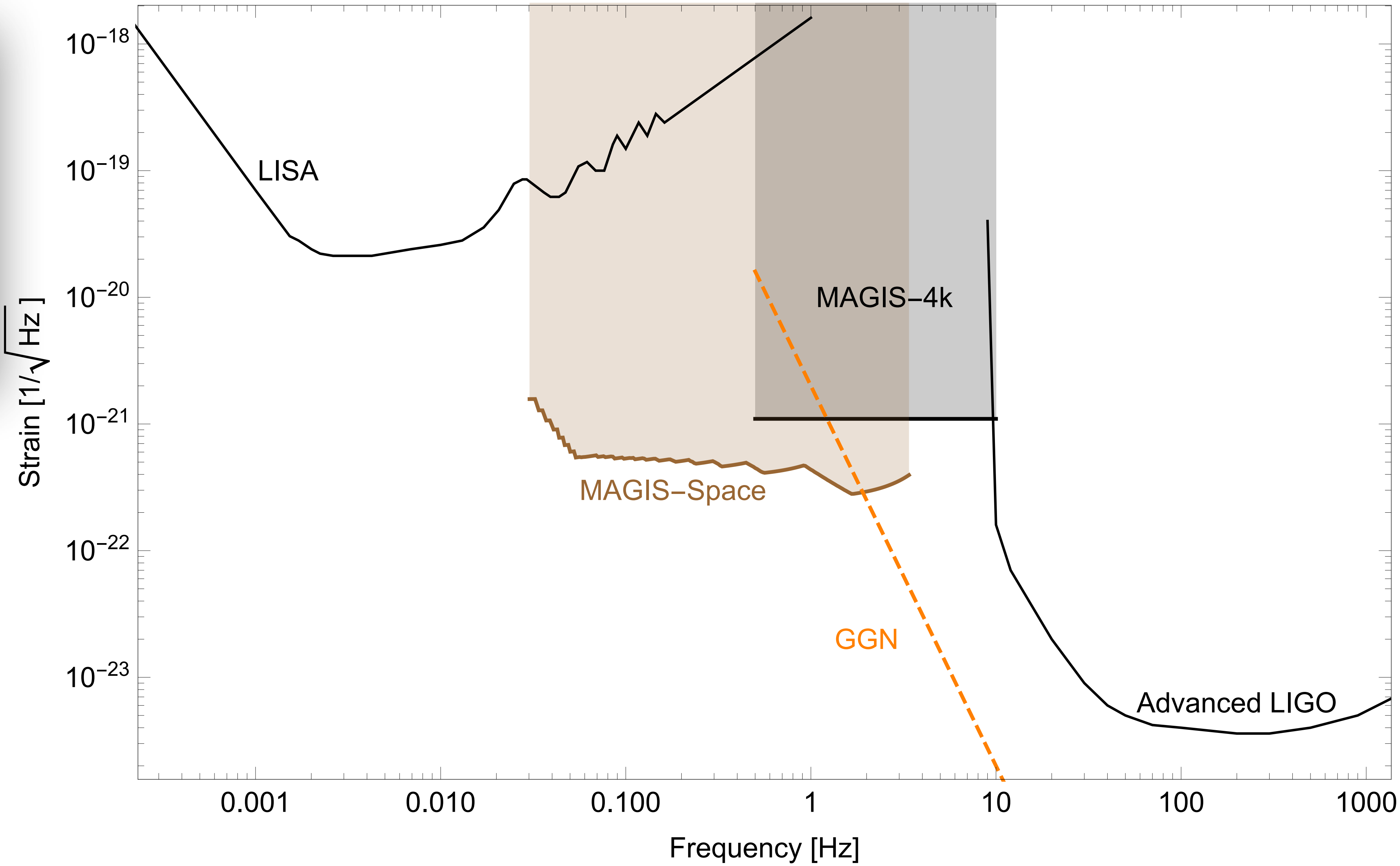
rest of talk I'll focus on science with these, use MAGIS as example

Atom Interferometry for Gravitational Waves

Future detectors (terrestrial + satellite) could access mid-frequency band:

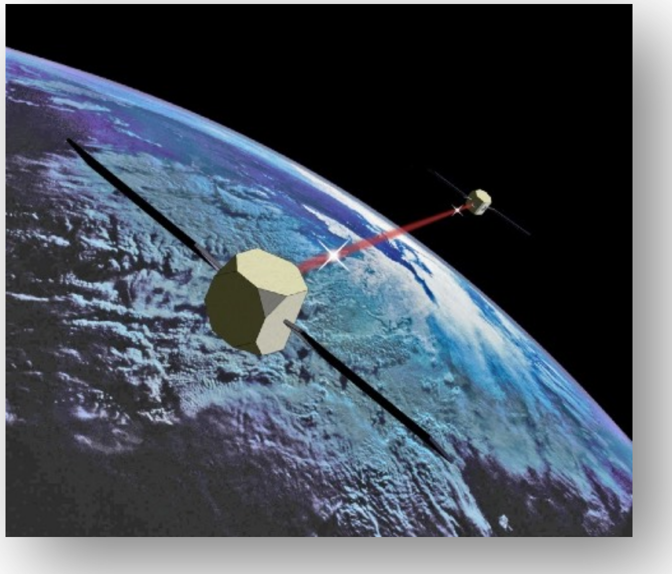


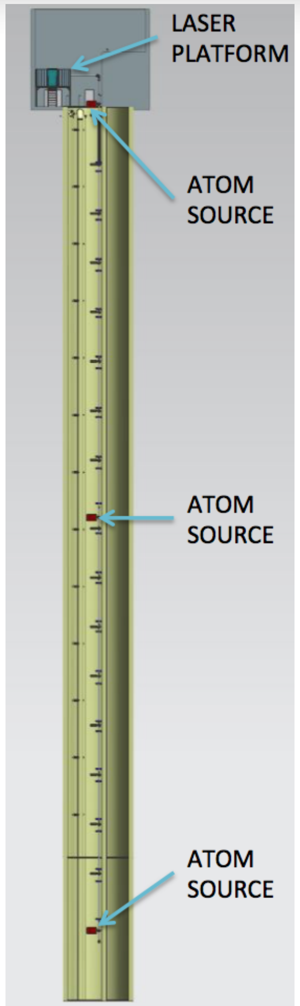


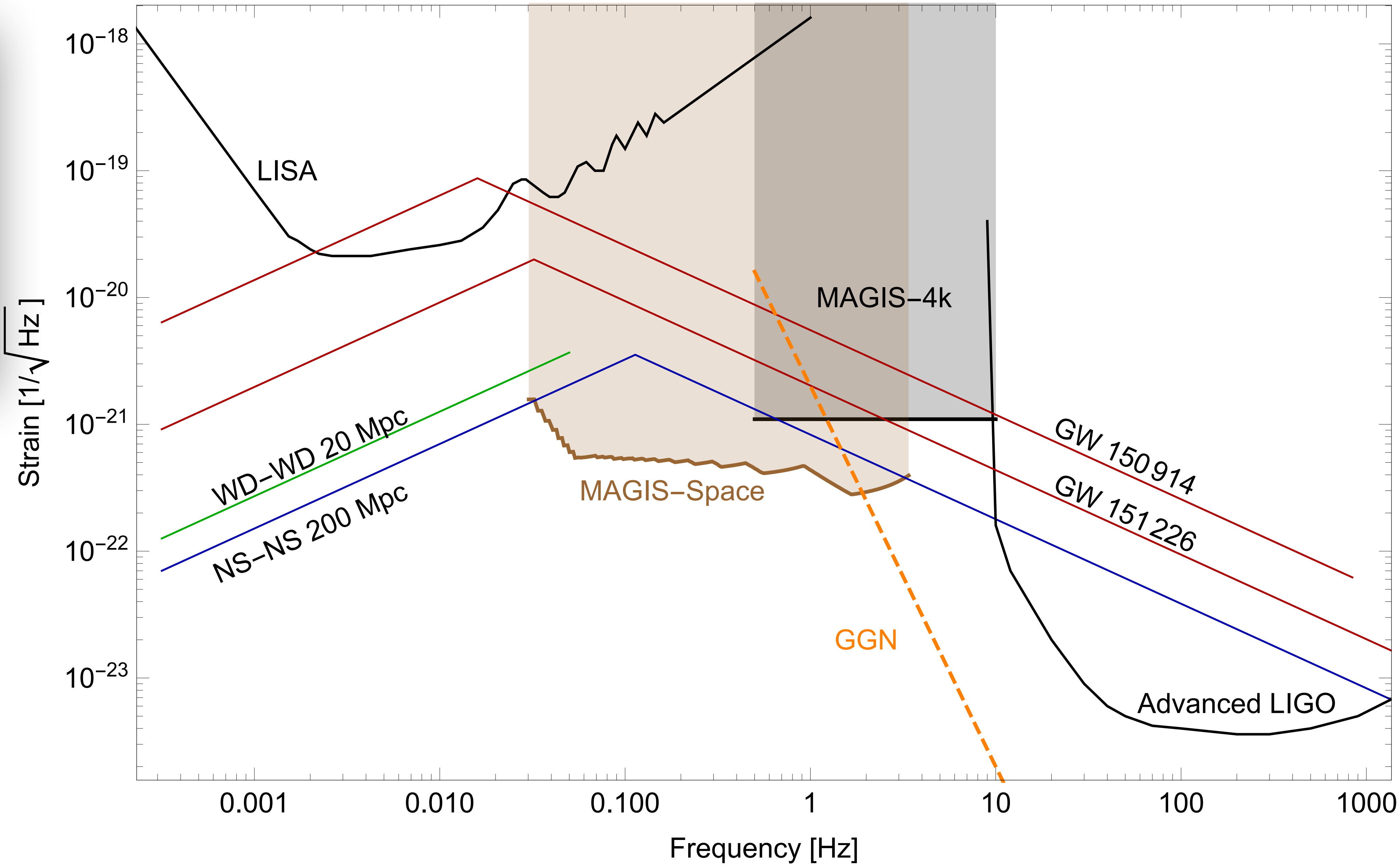


Atom Interferometry for Gravitational Waves

Future detectors (terrestrial + satellite) could access mid-frequency band:





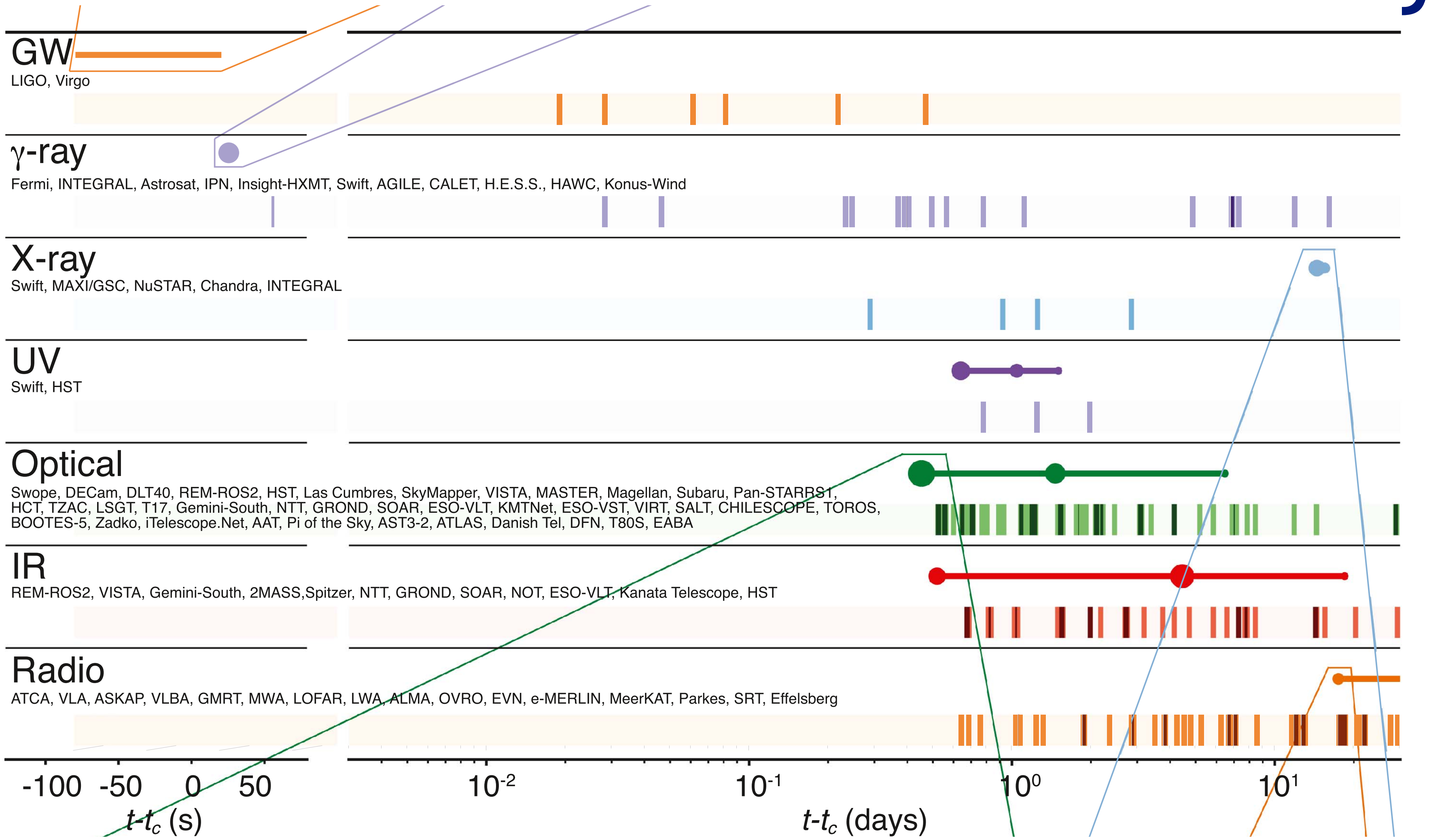


mid-frequency band is ideal for angular localization

predict merger time and location on sky (sub-degree)

PWG & S. Jung PRD **97** (2018)

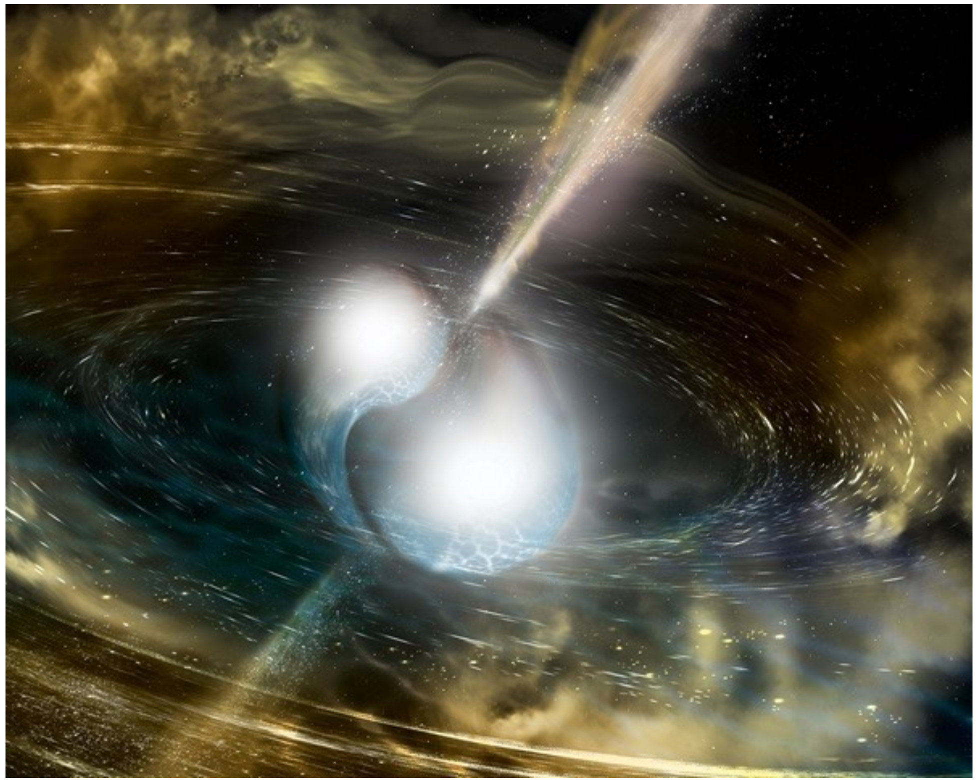
Neutron Star Mergers



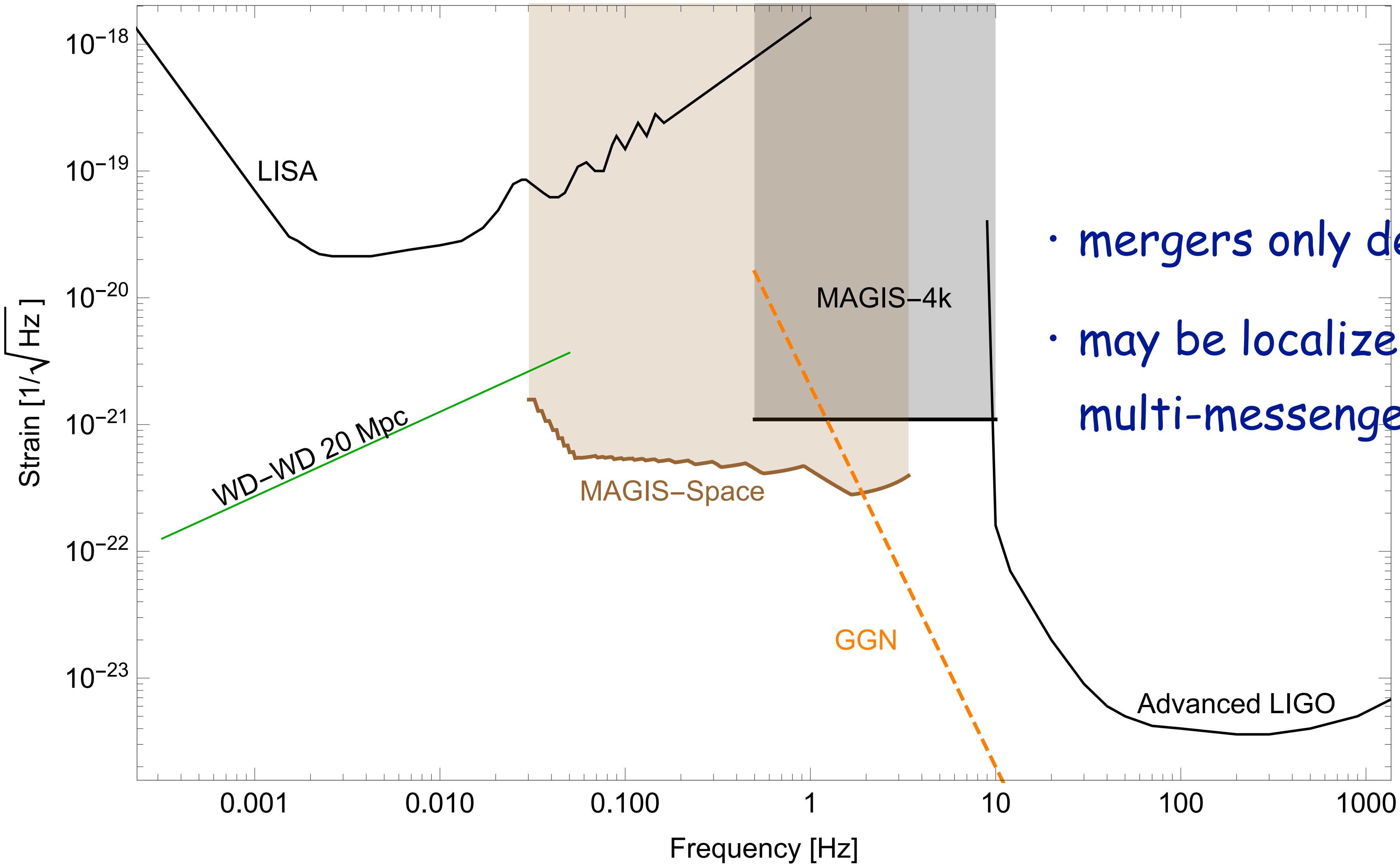
Ap.J.Lett. **848** (2017)

would allow EM telescopes to observe merger as it happens

e.g. learn more about NS mergers, kilonovae, origin of r-process elements, etc.



White Dwarf Mergers



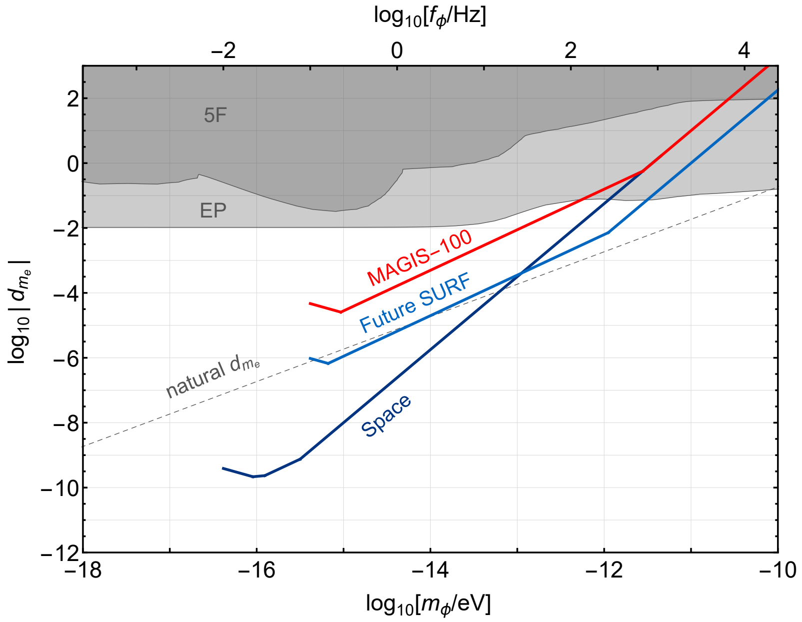
- mergers only detectable in mid-band
- may be localized and predicted in advance ➜ multi-messenger astronomy

What do we learn?

- What does a WD-WD collision look like? (Some of) Type Ia SN?
- measure rate, double degenerate vs single degenerate model of type Ia

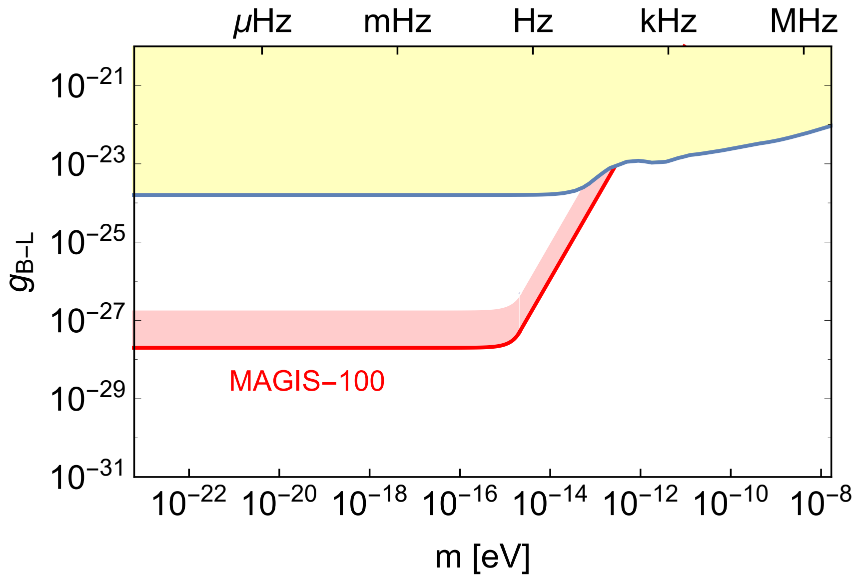
Dark Matter Detection with MAGIS

MAGIS can also detect ultralight dark matter (e.g. axions) with 3 complementary searches:



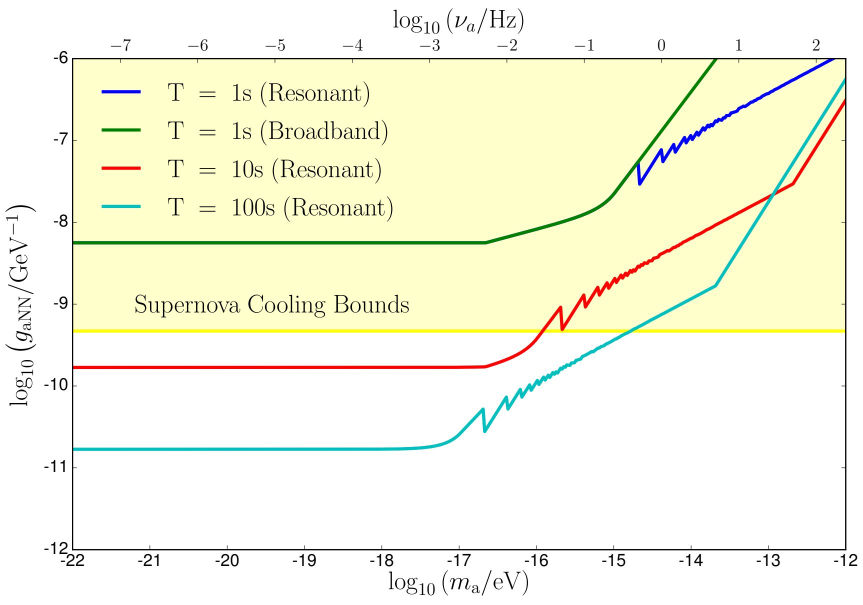
1. single-baseline "gravitational wave" search

   Arvanitaki, PWG, Hogan, Rajendran, Tilburg, PRD **97** (2018)



2. equivalence principle violation search

   PWG, Kaplan, Mardon, Rajendran, Terrano, PRD **93** (2016)



3. spin torque search

   PWG, Kaplan, Mardon, Rajendran, Terrano, Trahms, Wilkason, PRD **97** (2018)

Mid-band GW Science

Complementary to LIGO and LISA, observing with atoms in the mid-band may allow:

- Excellent angular resolution
- Identify upcoming NS (and BH) mergers allowing EM telescopes to observe event
- Standard siren measurements for cosmology: measure Hubble, dark energy EOS…
- Study WD mergers, type Ia supernovae, double degenerate vs single degenerate, etc.
- Measure BH spins and orbital eccentricities, learn about formation, heavier BH's
- Possibly early universe sources of GW's (inflation/reheating, cosmic strings, etc.)
- … Likely surprises too!

Gravitational waves will be major part of future of astrophysics and cosmology
must observe in all possible bands

These atomic detectors can also directly detect axion and dark photon dark matter

Atomic Clocks and Gravitational Waves at ~ 1-10 μHz

(PRELIMINARY)

with

Michael Fedderke

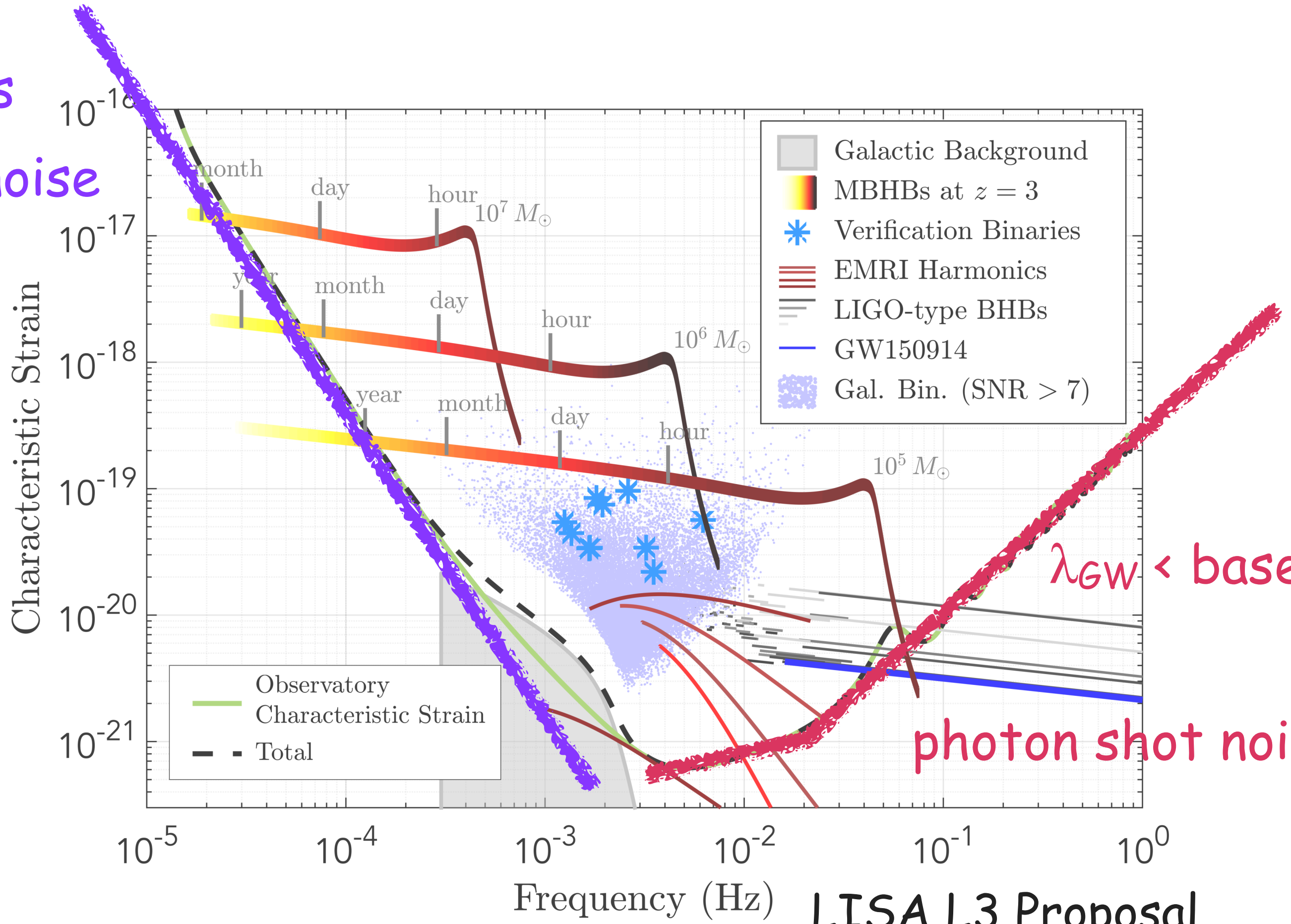
Surjeet Rajendran

Why the "μHz Gap"?

Why doesn't LISA reach lower frequencies?

proof mass acceleration noise

rises at low frequency

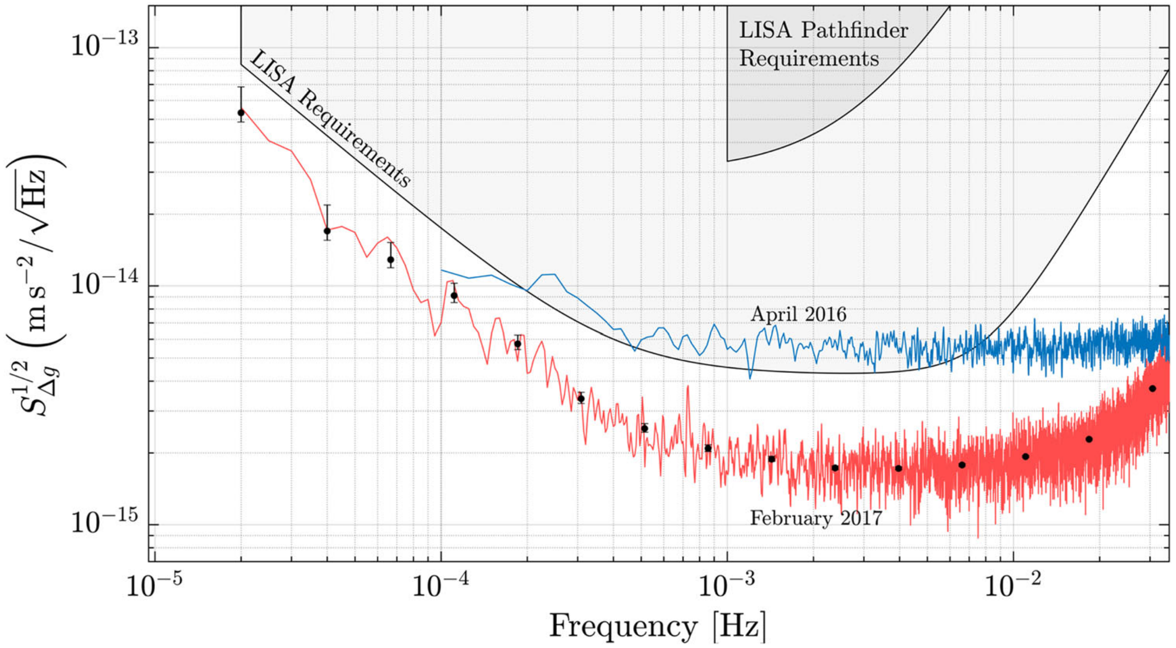


λ_{GW} < baseline

photon shot noise

LISA L3 Proposal

measured:



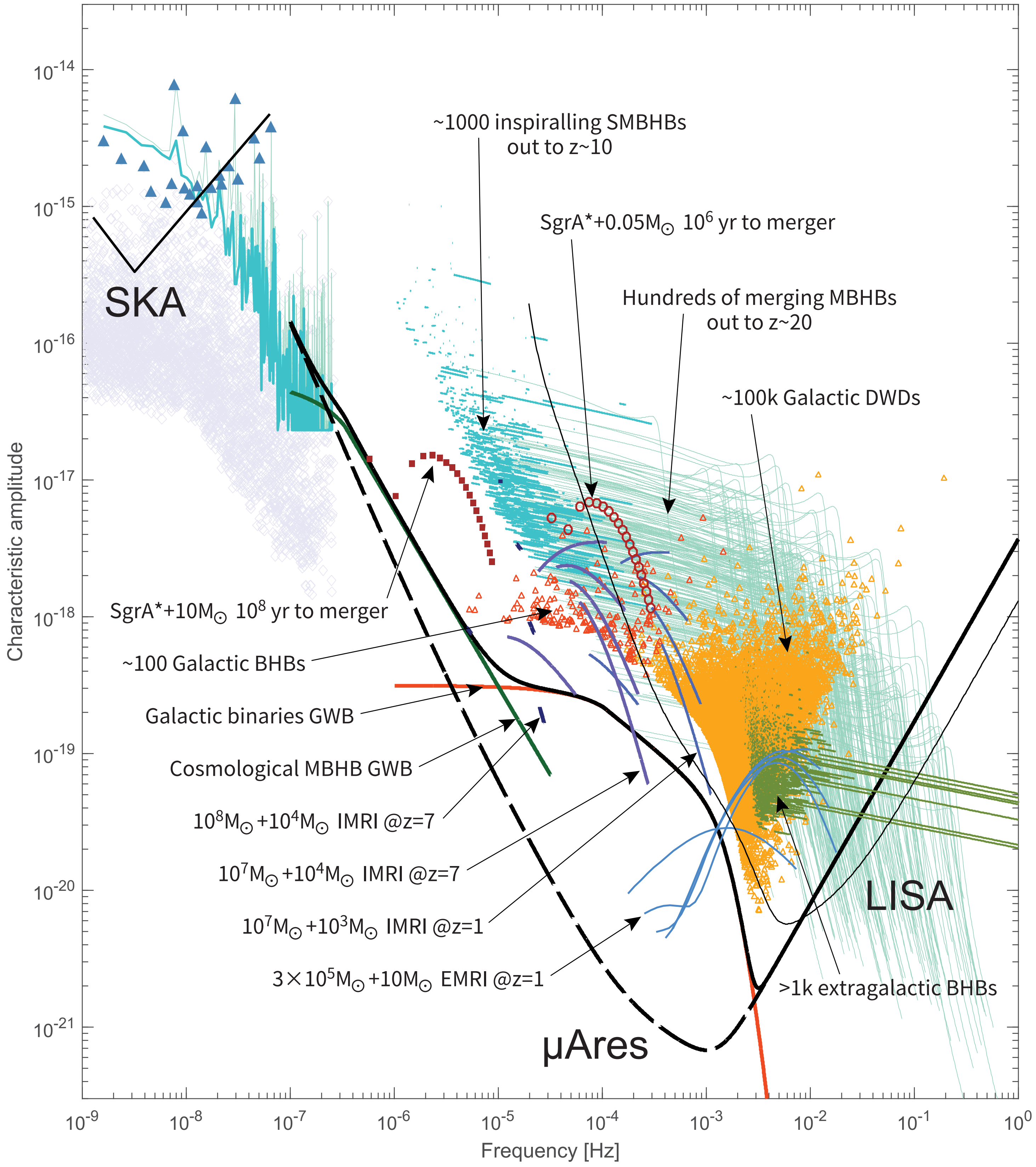
LISA Pathfinder PRL (2018)

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

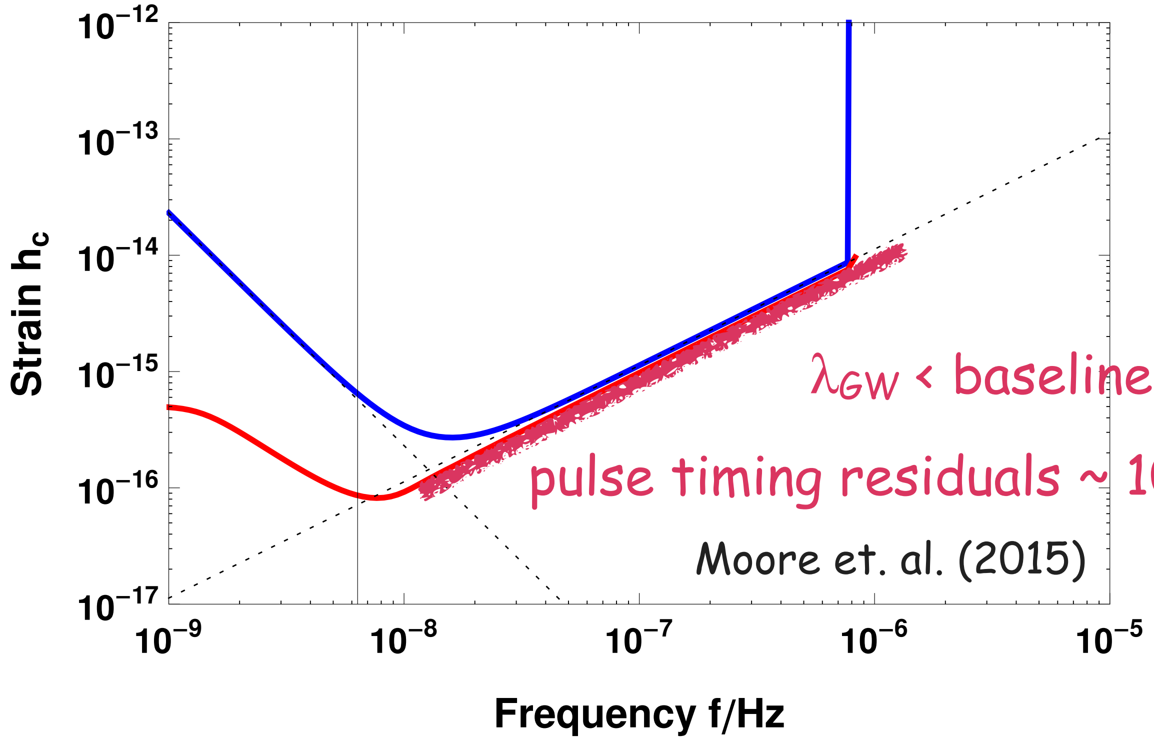
Other ways to observe this band?

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

Moore et. al. (2015)

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:

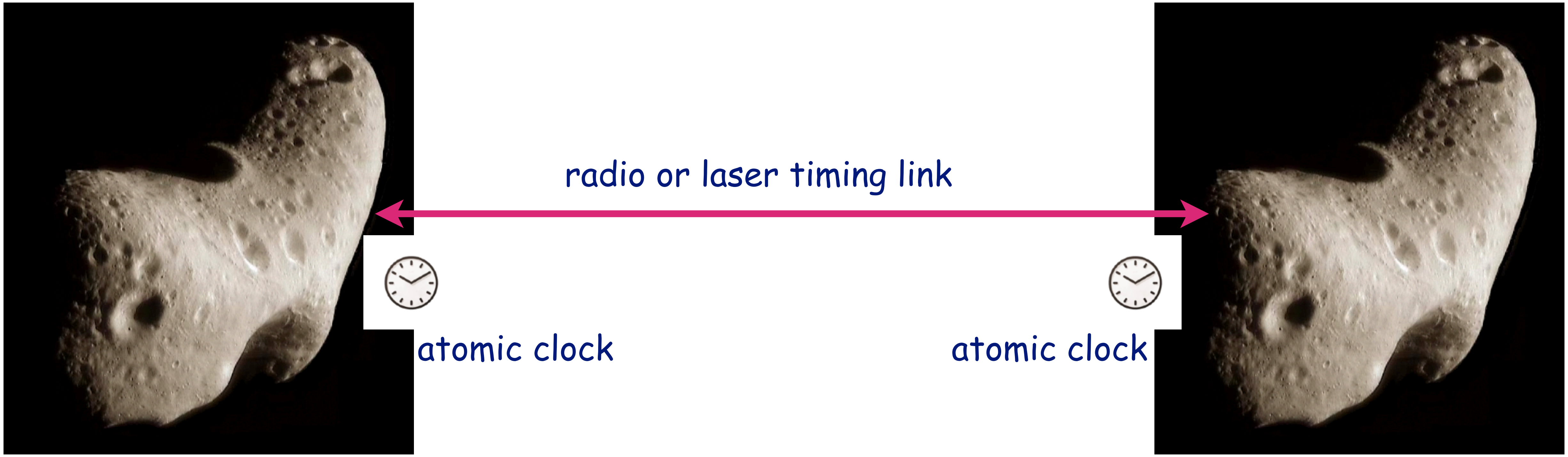
can we use asteroids?

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):



radio or laser timing link

atomic clock

atomic clock

433 Eros

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

Some Example Asteroids

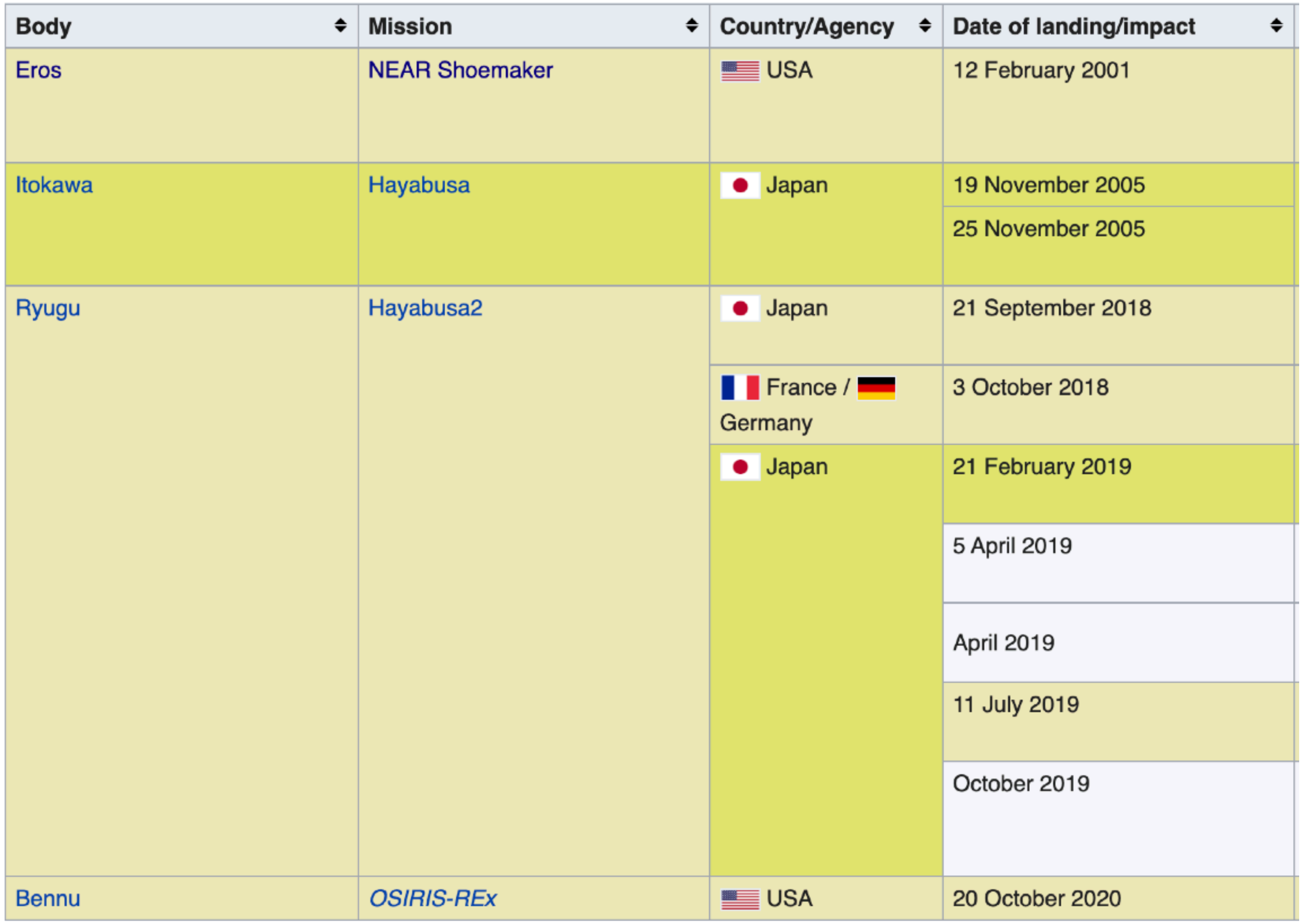
from NASA asteroid database:

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:

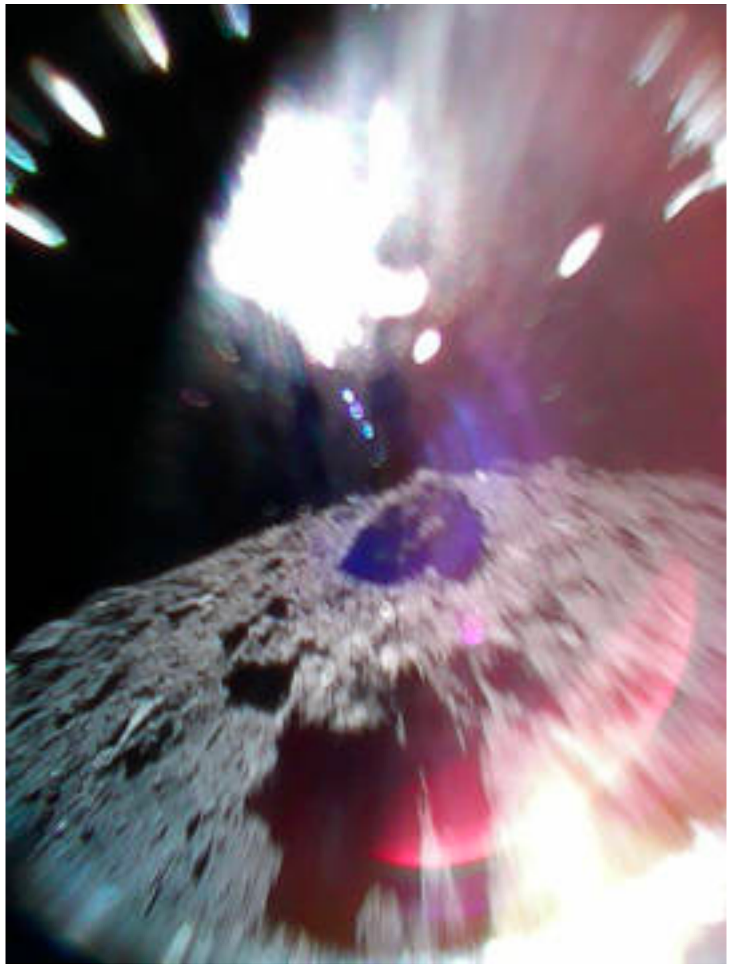


Body	Mission	Country/Agency	Date of landing/impact
Eros	NEAR Shoemaker	USA	12 February 2001
Itokawa	Hayabusa	Japan	19 November 2005 25 November 2005
Ryugu	Hayabusa2	Japan	21 September 2018
		France / Germany	3 October 2018
		Japan	21 February 2019
			5 April 2019
			April 2019
			11 July 2019
			October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

$$a \sim 10^{-13}\,\frac{\mathrm{m}}{\mathrm{s}^2}$$

reduced by larger and farther asteroid

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

solar intensity fluctuations measured

at relevant frequencies

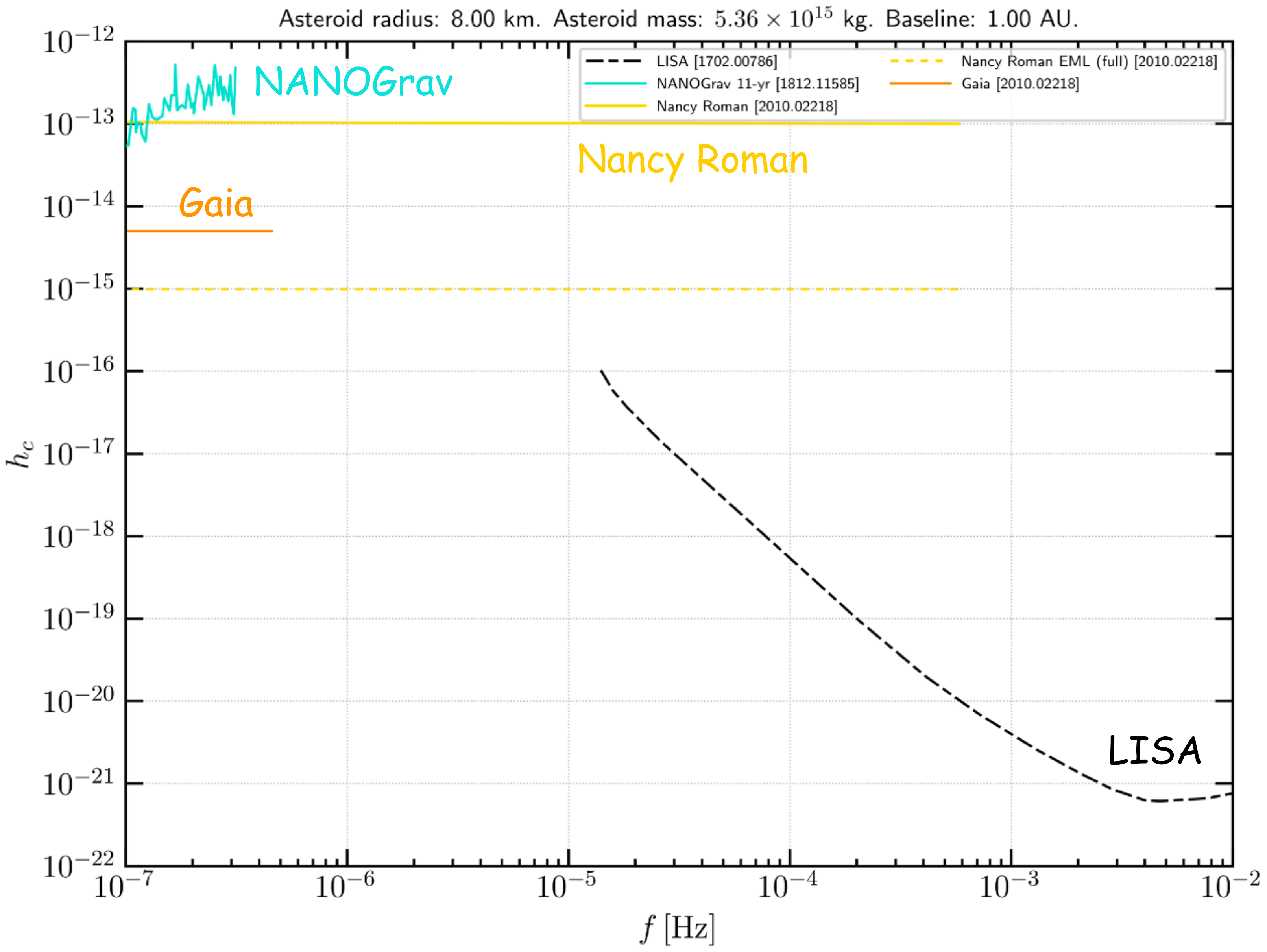
strain ASD:

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

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

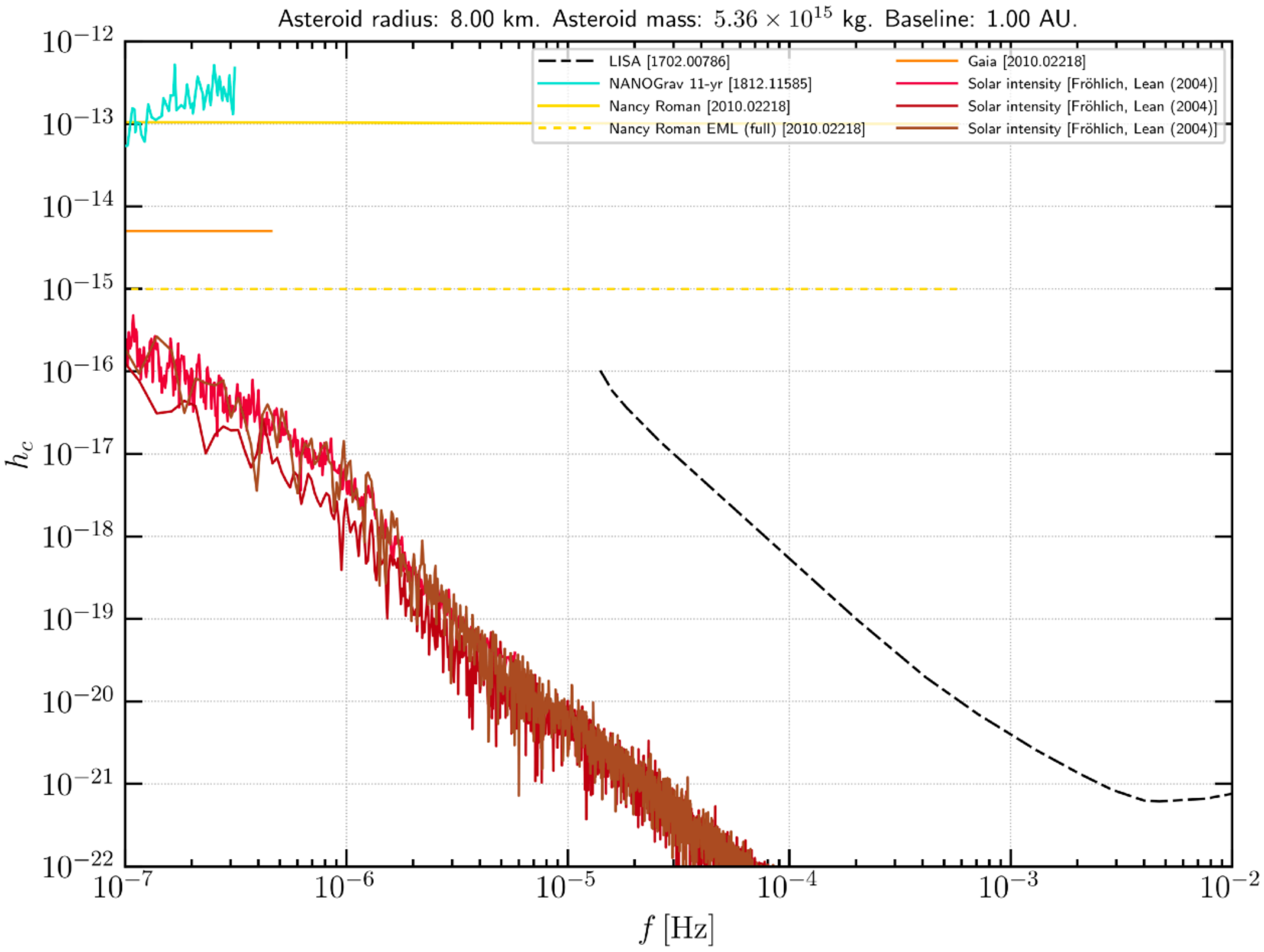
diameters > 1 km give sufficient noise suppression

Unexplored GW Band



Solar Intensity Acceleration Noise

Measured solar intensity fluctuations, applied to example asteroid



strain ASD:

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

measured solar intensity PSD

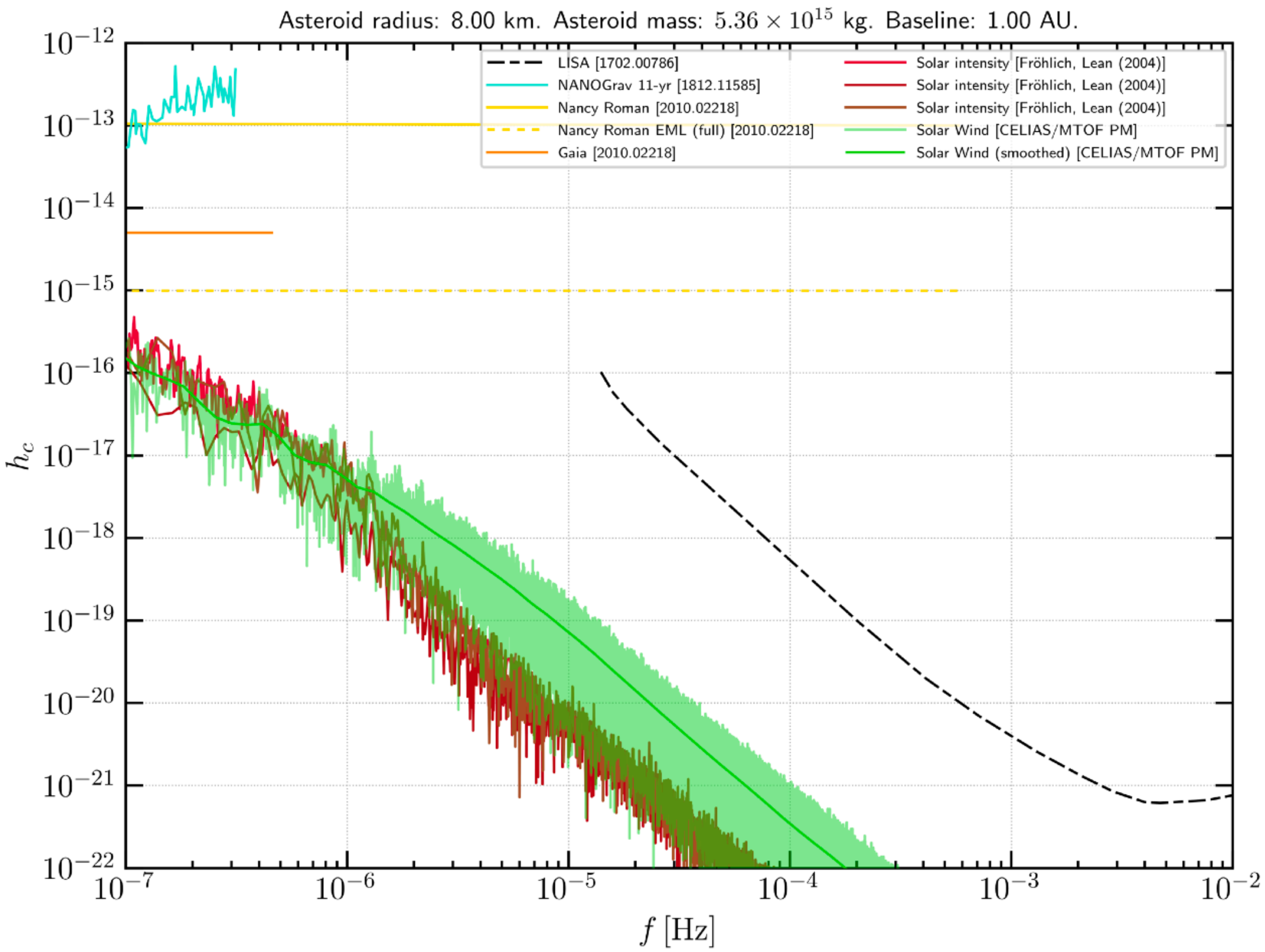
Fröhlich & Lean (2004)

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:

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

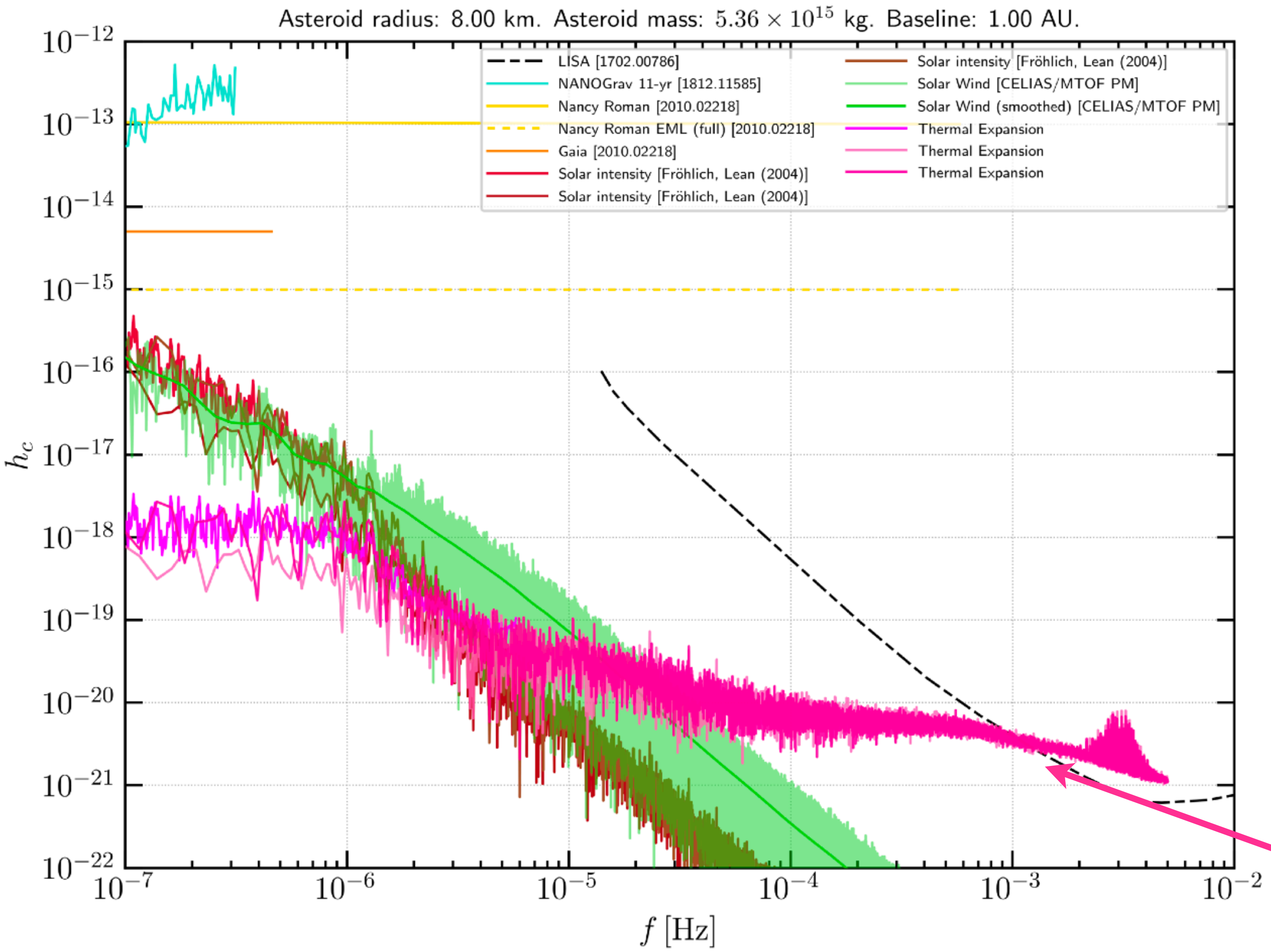
measured solar wind PSD

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)

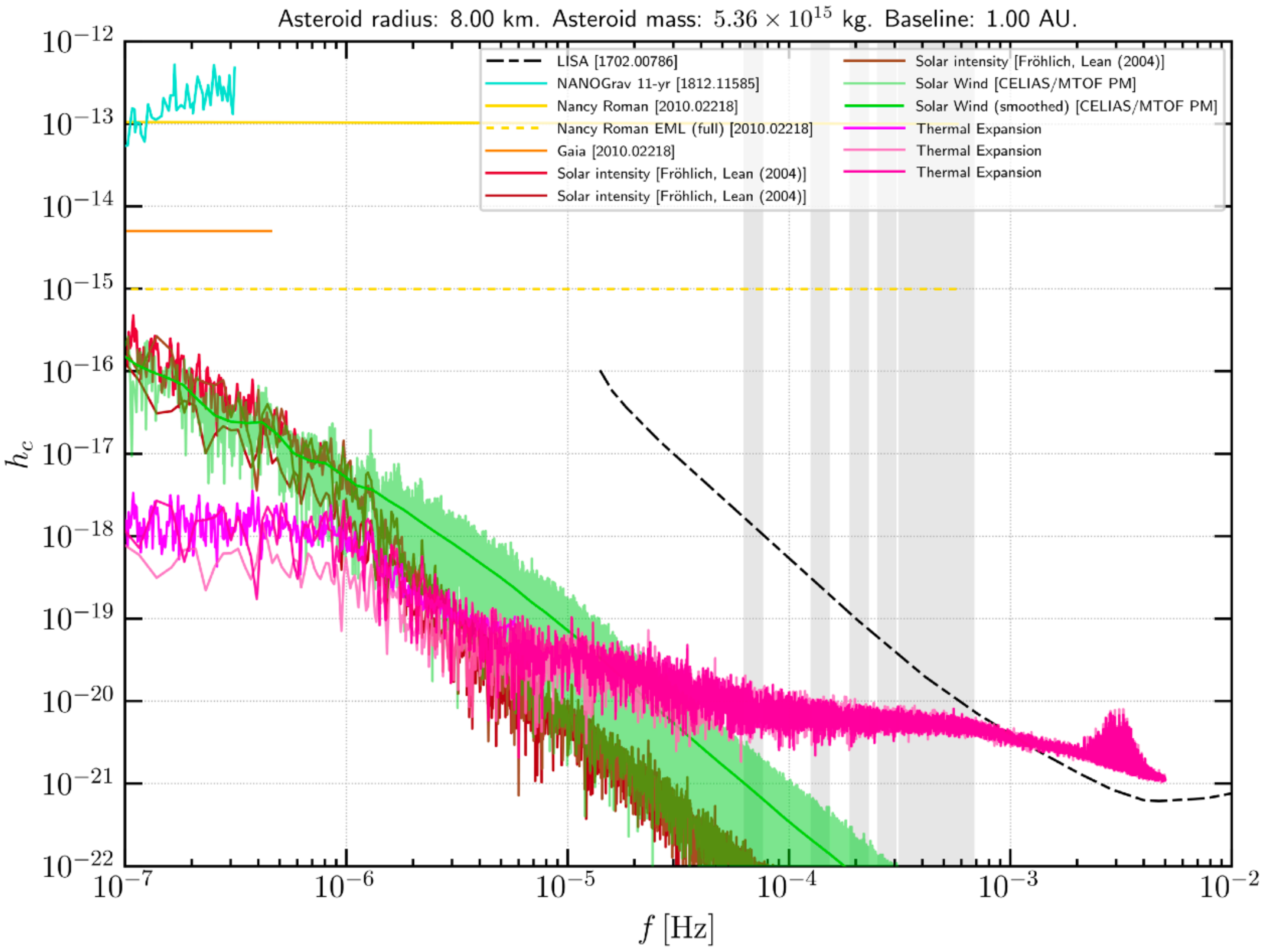
relevant noise is solar fluctuations at our frequencies

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

surface height fluctuation is noise

Rotation Noise

Asteroid rotation periods generally ~ few hours



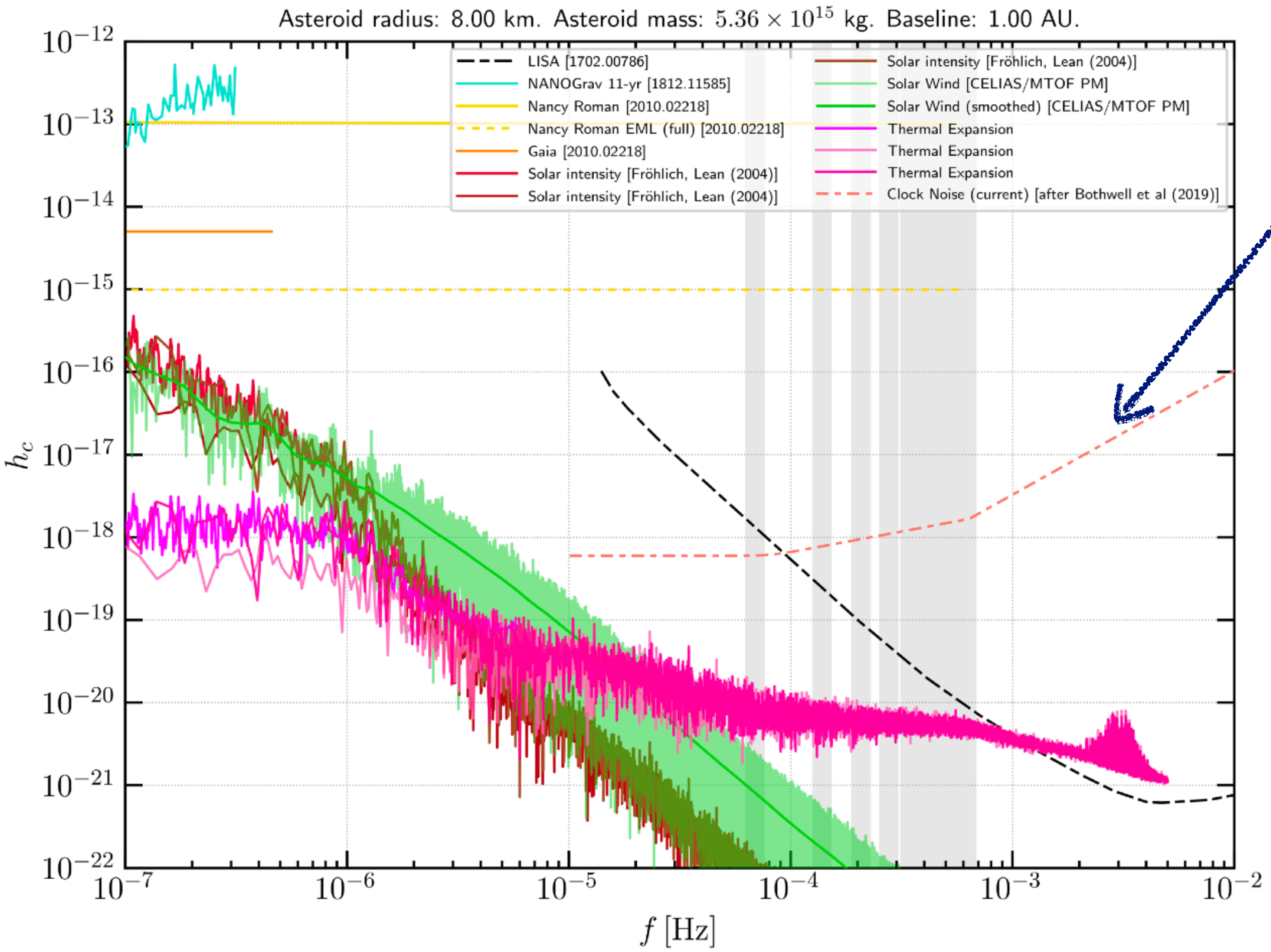
removes higher frequency bands

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

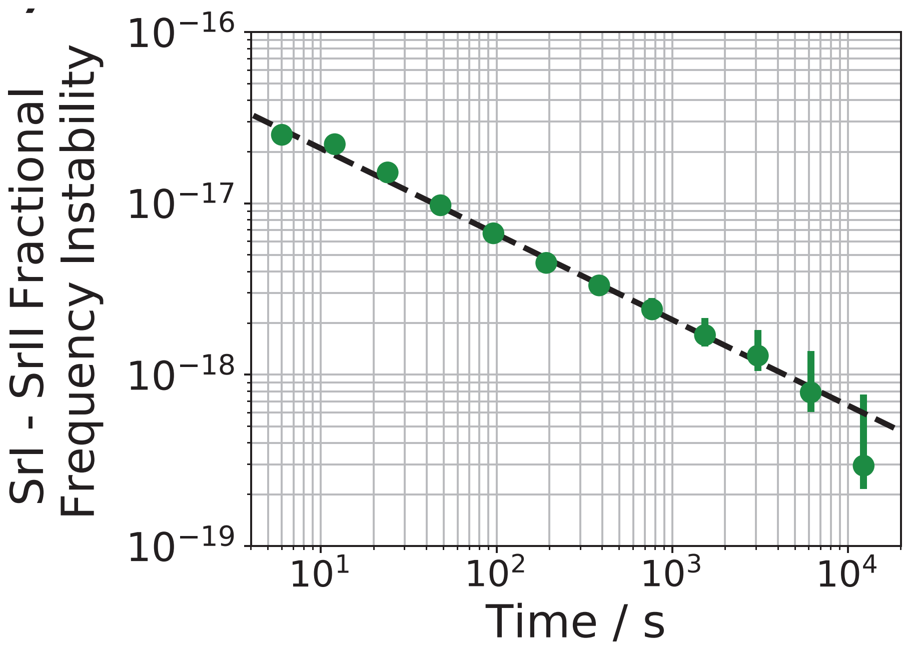
asteroid as inertial proof mass allows significant improvement at low frequencies

Clock Noise

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



translated current atomic clock



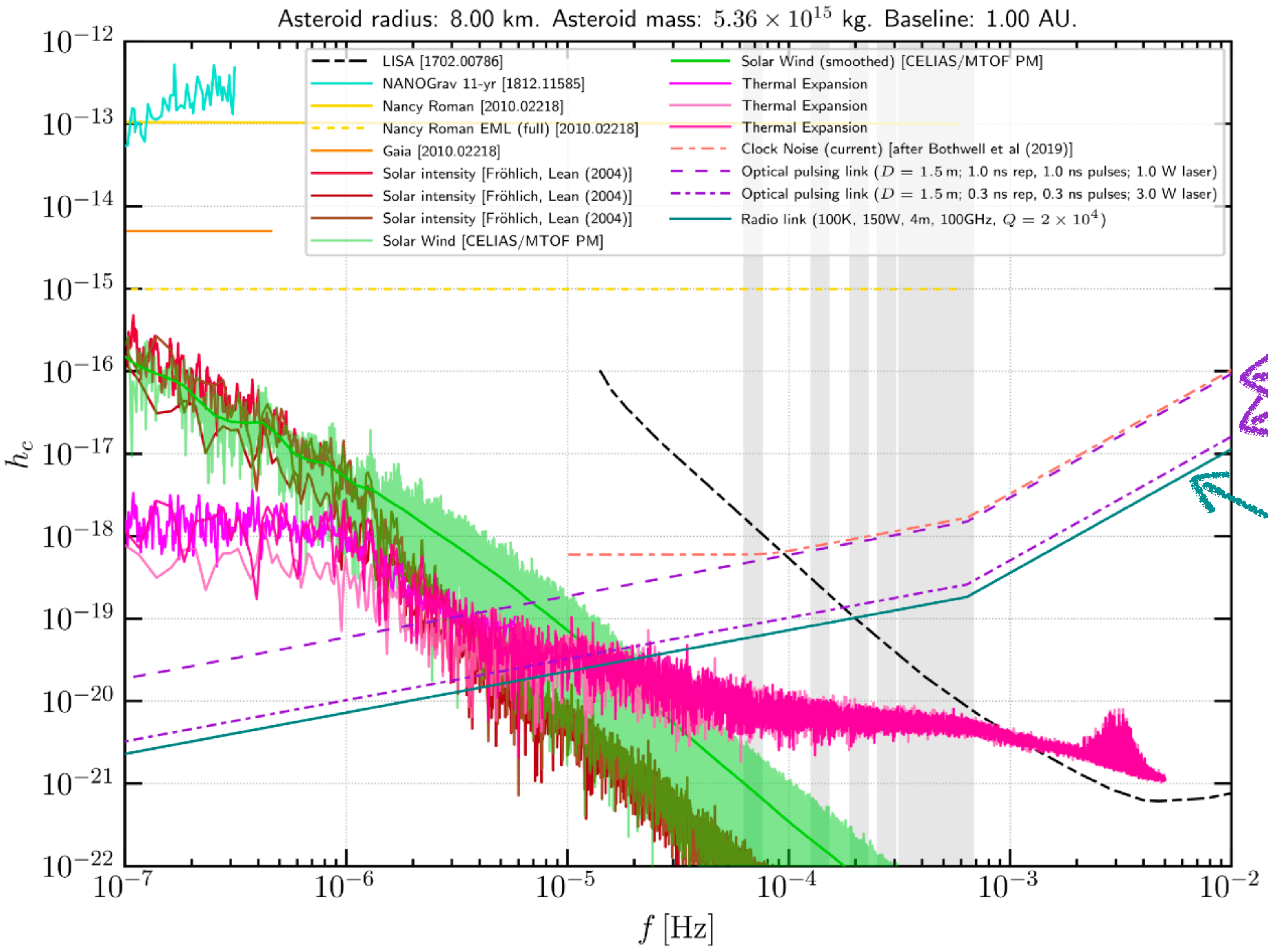
Bothwell et. al. (2019)

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

laser pulsing

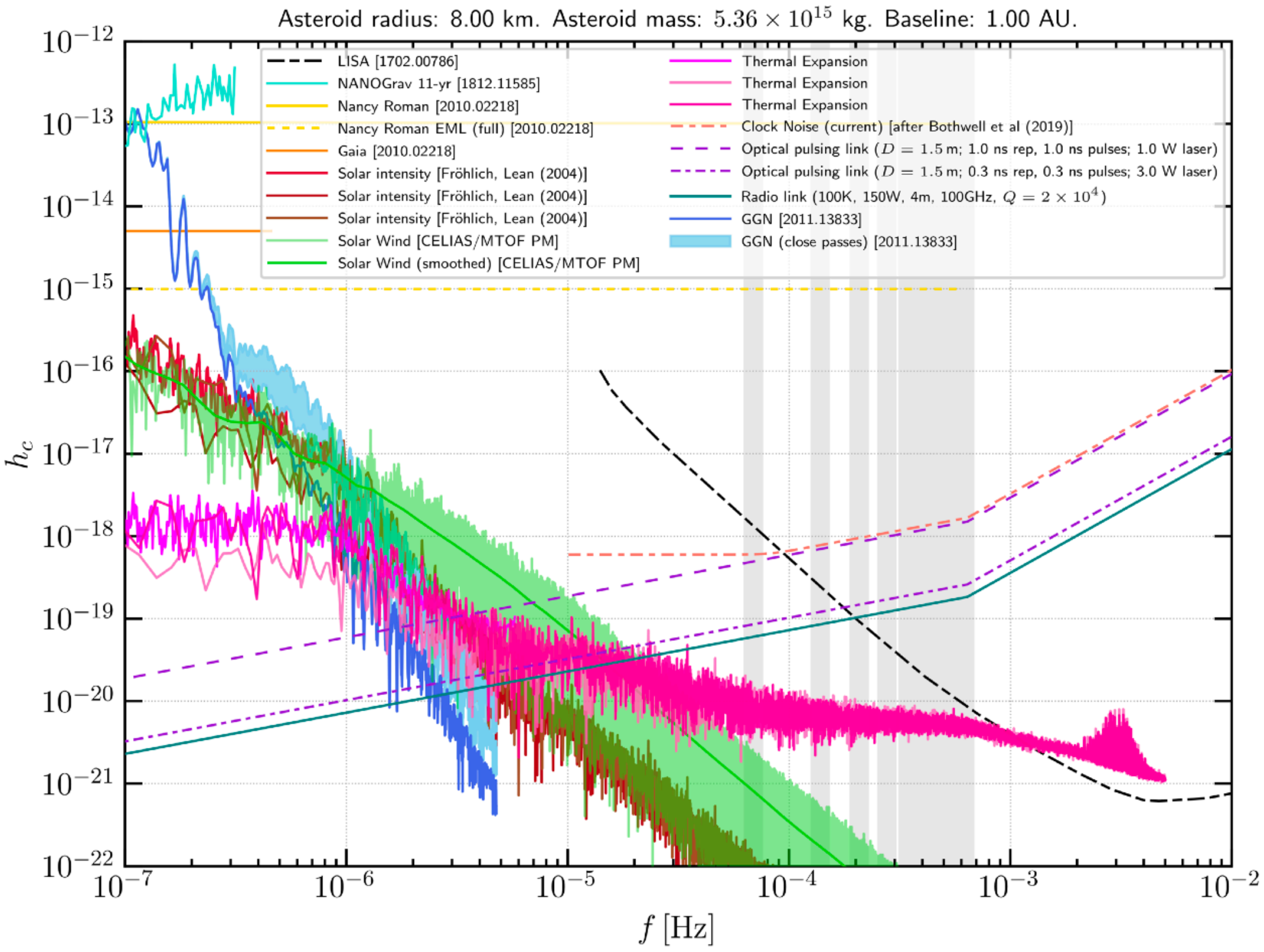
radio interferometry

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

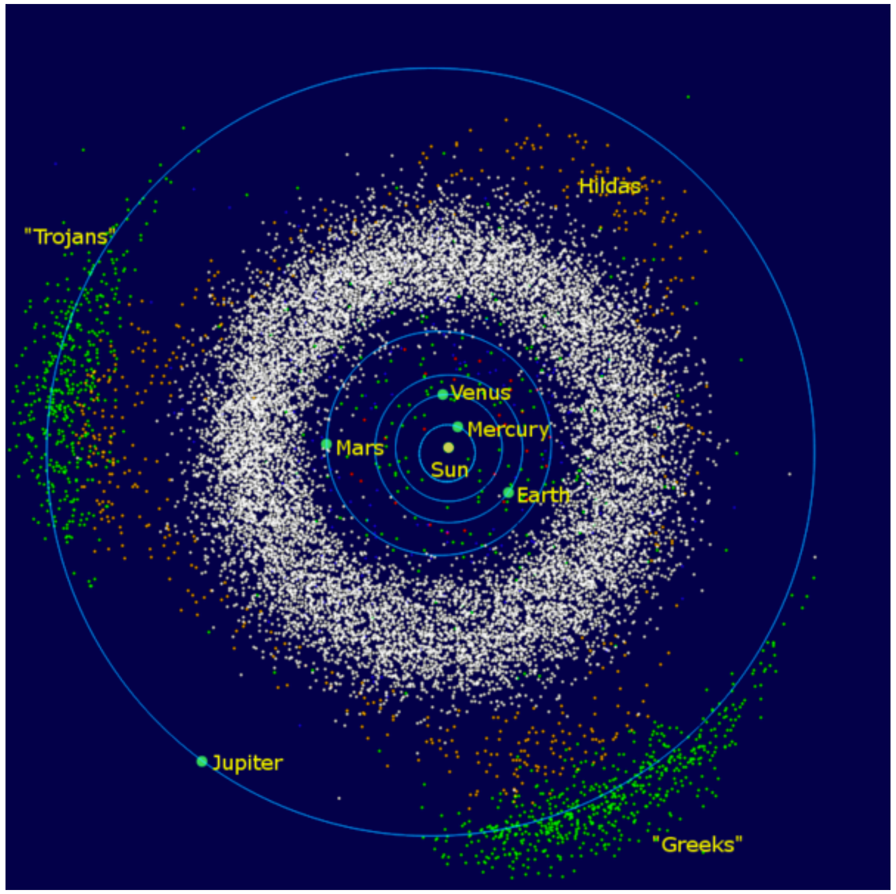
Asteroid Gravity Gradient Noise

predominantly around orbital period (of detector) ~ few years

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



Asteroid radius: 8.00 km. Asteroid mass: 5.36×10^{15} kg. Baseline: 1.00 AU.

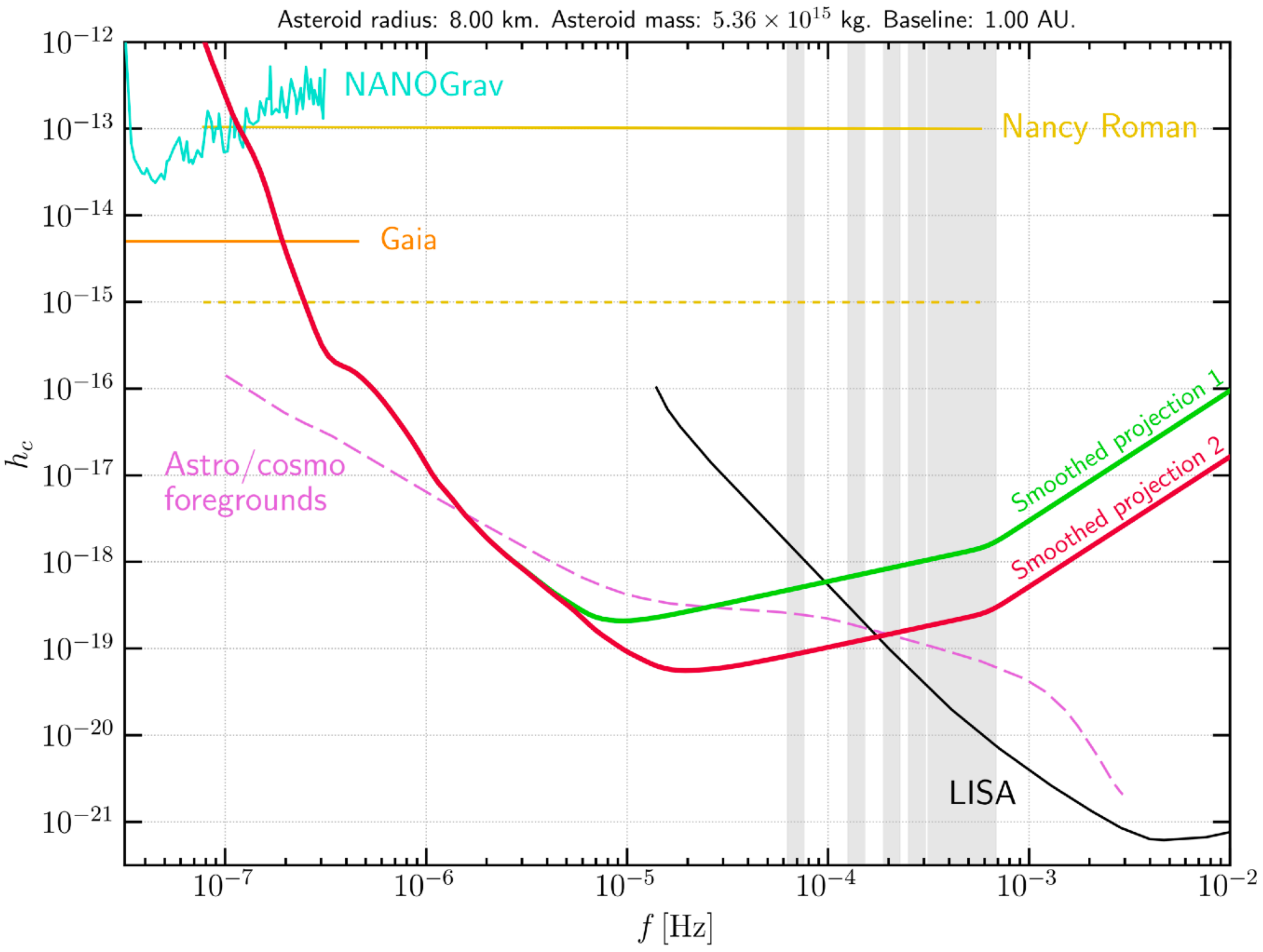


dedicated simulation using NASA JPL asteroid catalog, supplemented with estimate for higher frequency "close pass" noise of unmodeled asteroids using e.g. lunar crater data

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

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!

Examples of Quantum Technologies for Fundamental Physics

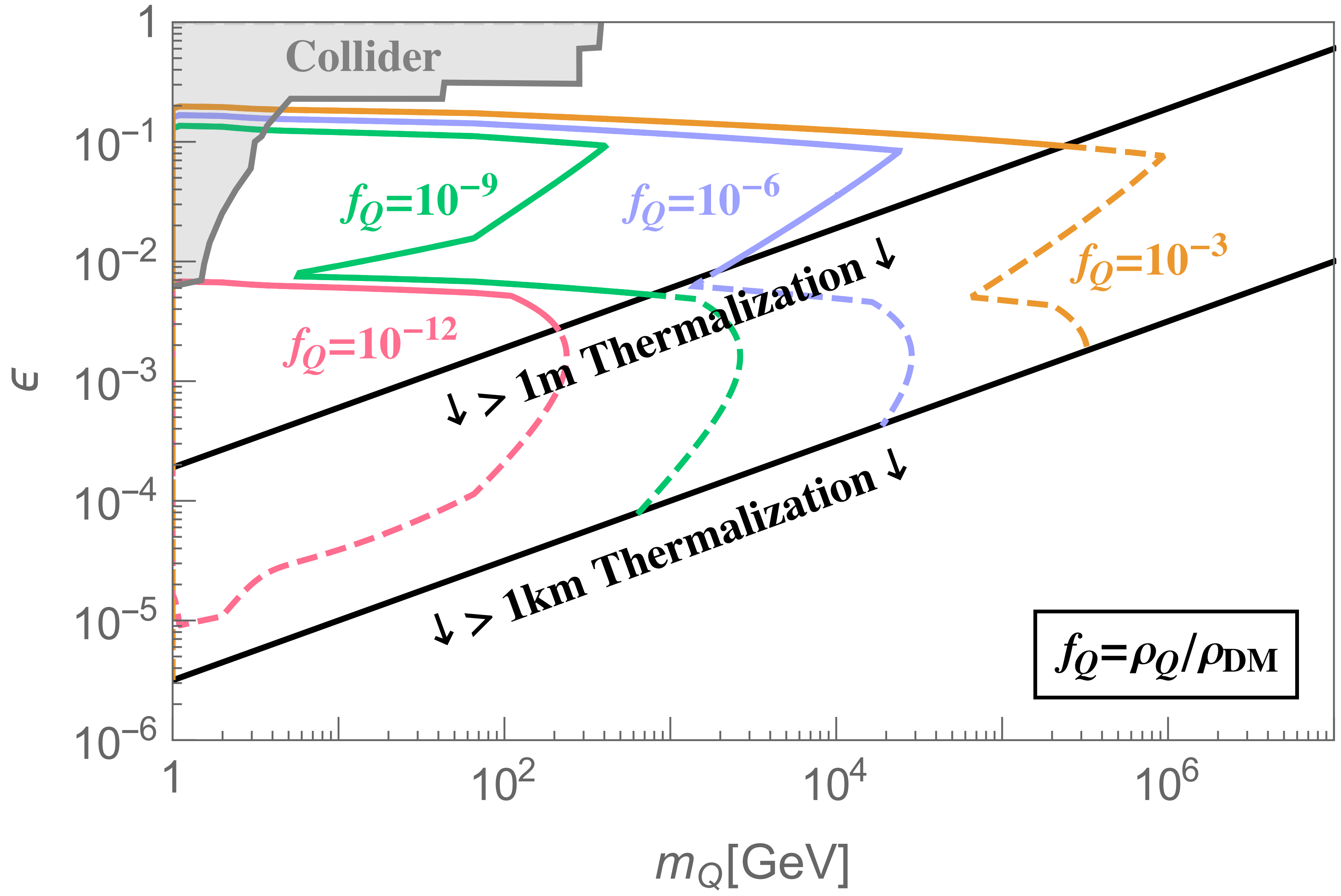
1. Millicharged Particles and Trapped Ions (in progress)
2. Atomic Interferometry for Gravitational Waves ~ Hz
3. Asteroids and Atomic Clocks for Gravitational Waves at ~ μHz (in progress)

Many exciting talks to come!

Backup Slides

Dark Matter Detection

Bounds as a fraction of dark matter:



to appear