New techniques for observing gravitational waves

Peter Graham

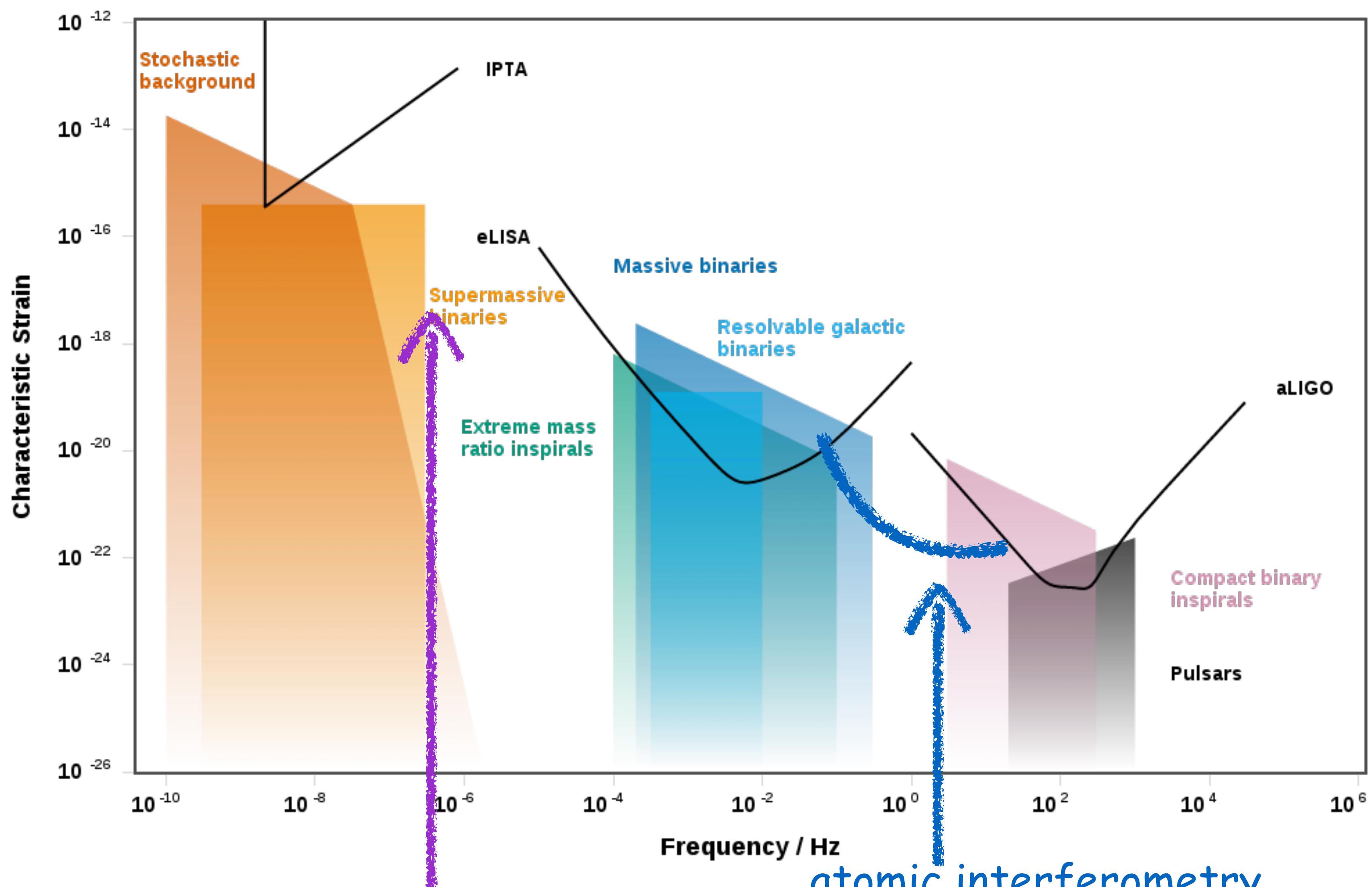
Stanford

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

atomic interferometry
(MAGIS, clocks, MIGA,
AION...)

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

Outline

1. Gravitational wave detection with atom interferometry ~ Hz band

2. New proposal for μHz band using atomic clocks (preliminary)

Gravitational Wave Detection with Atom Interferometry

with

Savas Dimopoulos
Jason Hogan
Mark Kasevich
Surjeet Rajendran

PRD **94** (2016) arXiv:1606.01860
PRL **110** (2013) arXiv:1206.0818
GRG **43** (2011) arXiv:1009.2702
PLB **678** (2009) arXiv:0712.1250
PRD **78** (2008) arXiv:0806.2125

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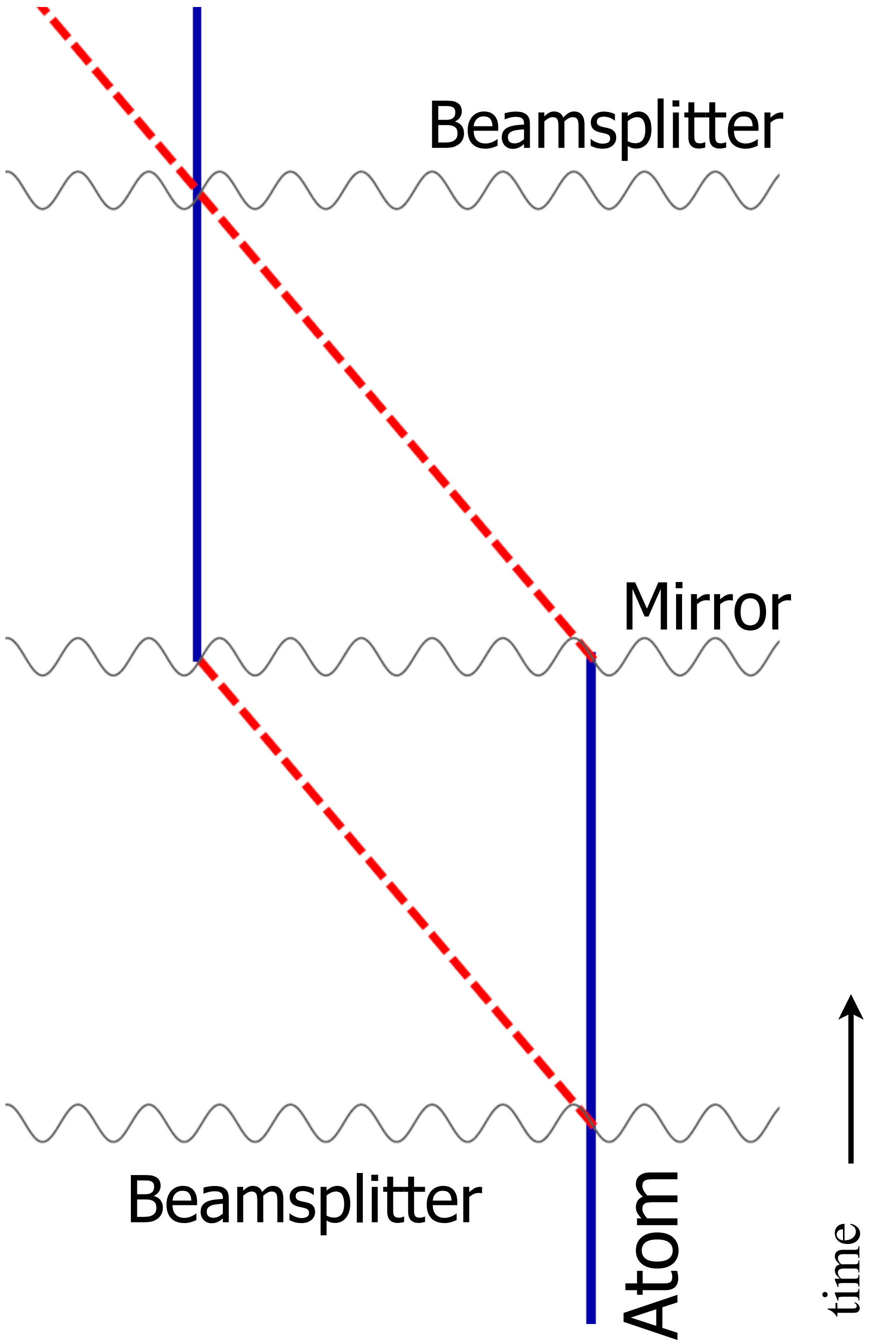
DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

Atom Interferometry



two halves recombined and
final phase difference measured

laser pulse coherently split each atom's
wavefunction, and separate the halves

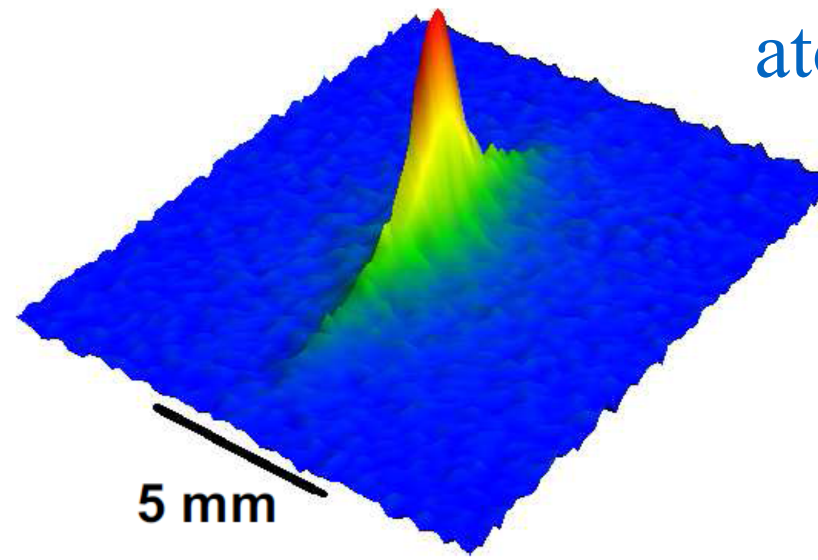
start with ultracold cloud of atoms in free fall

Experimental Demonstrations

(Kasevich and Hogan groups)

Stanford 10 m Test Facility

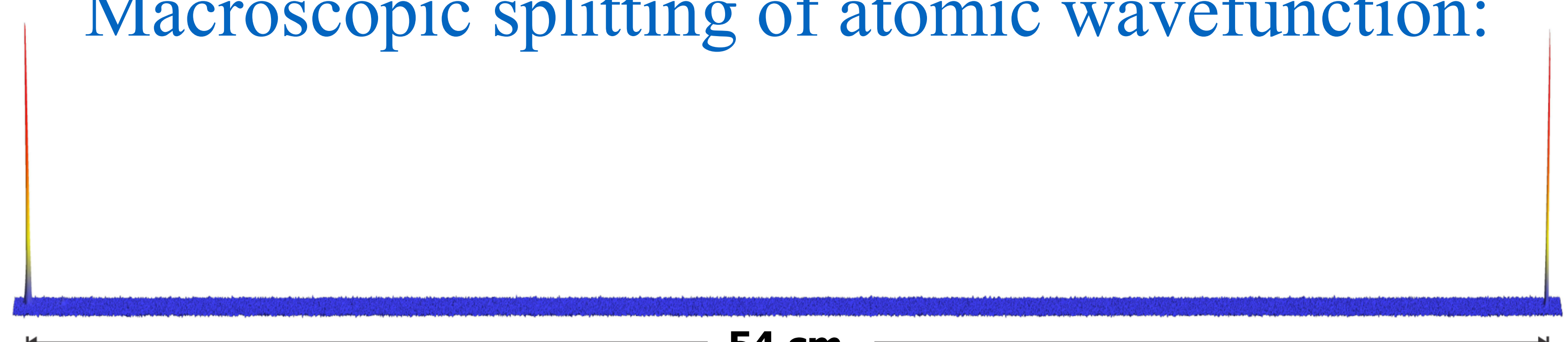
demonstrate necessary technologies (in Rb):



atom cooling

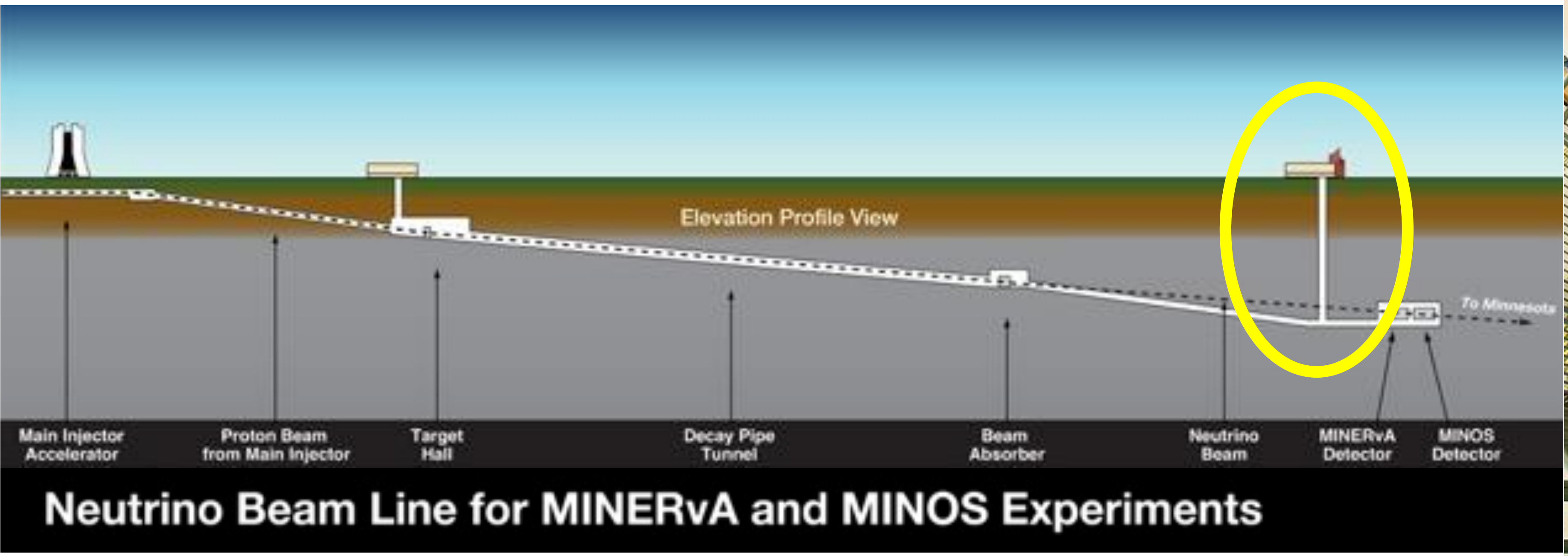
→ 50 pK

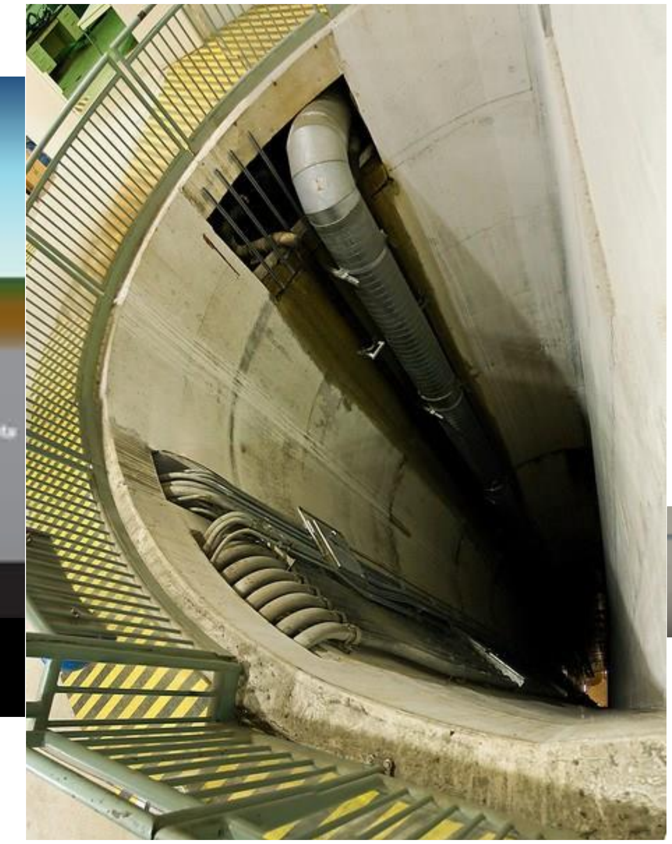
Macroscopic splitting of atomic wavefunction:



Kovachy et. al, *Nature* (2015)

MAGIS-100 at Fermilab





- atom interferometers (like clocks) measure light travel time
- 100m Sr atom interferometer drop tower
- Detect ultralight dark matter from oscillation of energy levels
- Demonstrator for future gravitational wave detectors (terrestrial ~km scale, and satellite)
- Under construction!

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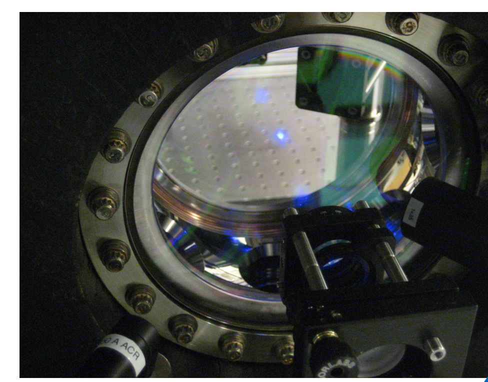
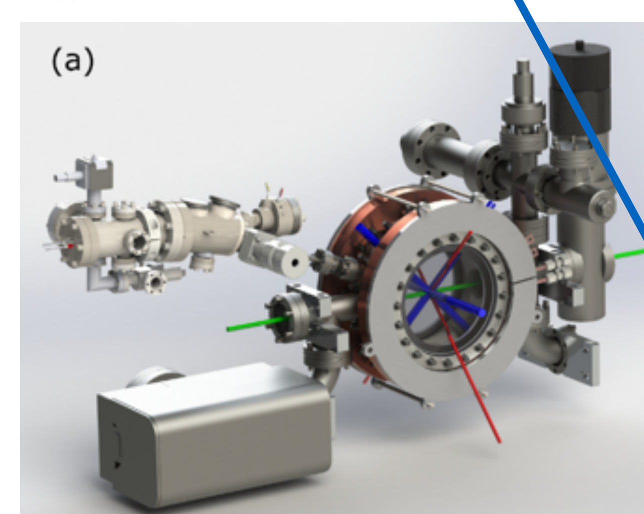
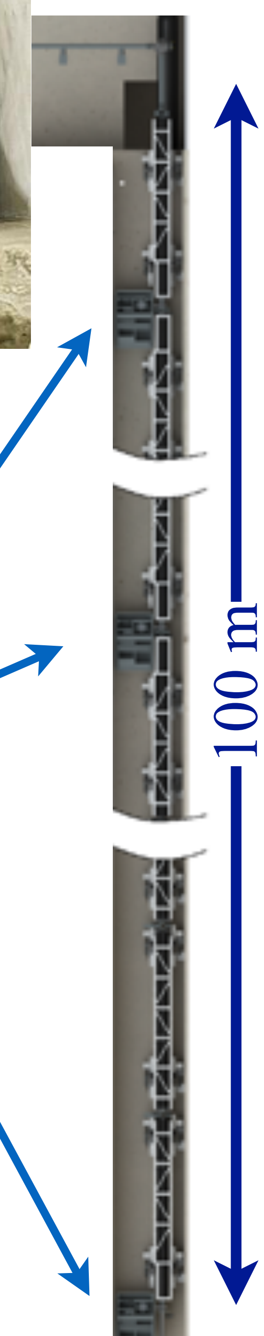


Sr atom sources

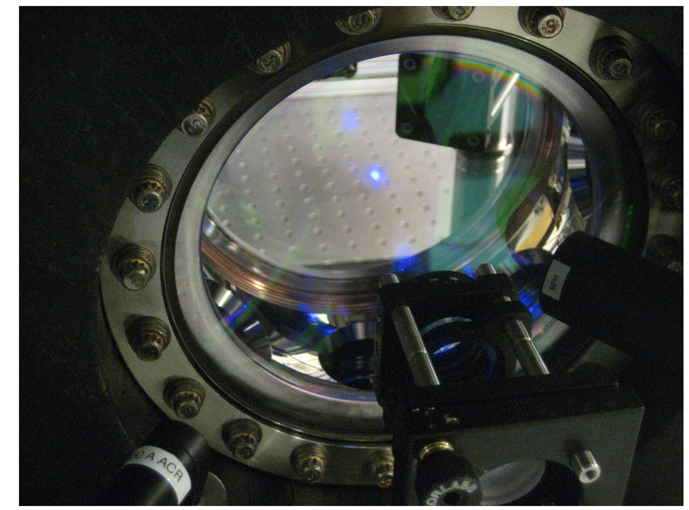


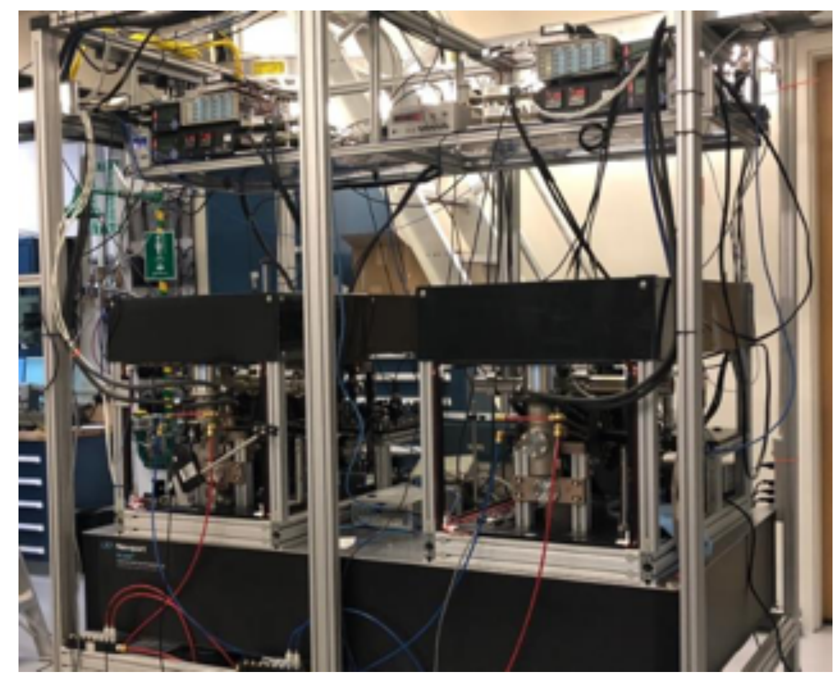


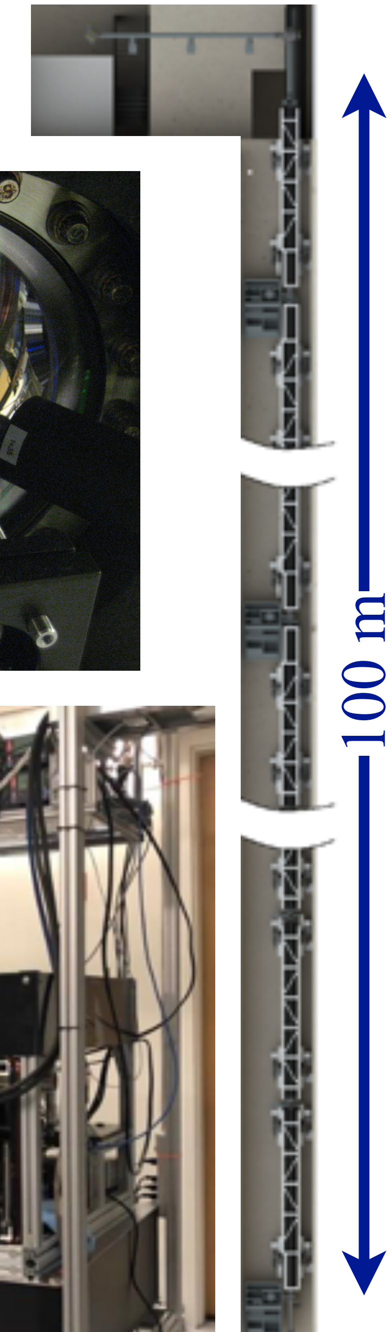
MAGIS-100 Collaboration

Spokesperson: Jason Hogan

Mahiro Abe
Philip Adamson
Marcel Borcean
Daniela Bortoletto
Kieran Bridges
Samuel Carman
Swapan Chattopadhyay
Jonathon Coleman
Noah Curfman
Joseph Lykken
Kenneth DeRose
Tejas Deshpande
Savas Dimopoulos
Christopher Foot
Josef Frisch
Benjamin Garber
Steve Geer
Valerie Gibson
Jonah Glick
Peter Graham
Steve Hahn
Roni Harnik
Leonie Hawkins
Sam Hindley
Jason Hogan
Yijun Jiang
James Santucci
Mark Kasevich
Ronald Kellett
Mandy Kiburg
Tim Kovachy
John March-Russell
Jeremiah Mitchell
Martin Murphy
Megan Nantel
Lucy Nobrega
Robert Plunkett
Surjeet Rajendran
Roger Romani
Jan Rudolph
Natasha Sachdeva
Murtaza Safdari
Ariel Schwartzman
Ian Shipsey
Hunter Swan
Linda Valerio
Arvydas Vasonis
Yiping Wang
Thomas Wilkason







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SLAC
Northwestern University
JOHNS HOPKINS UNIVERSITY
UNIVERSITY OF OXFORD
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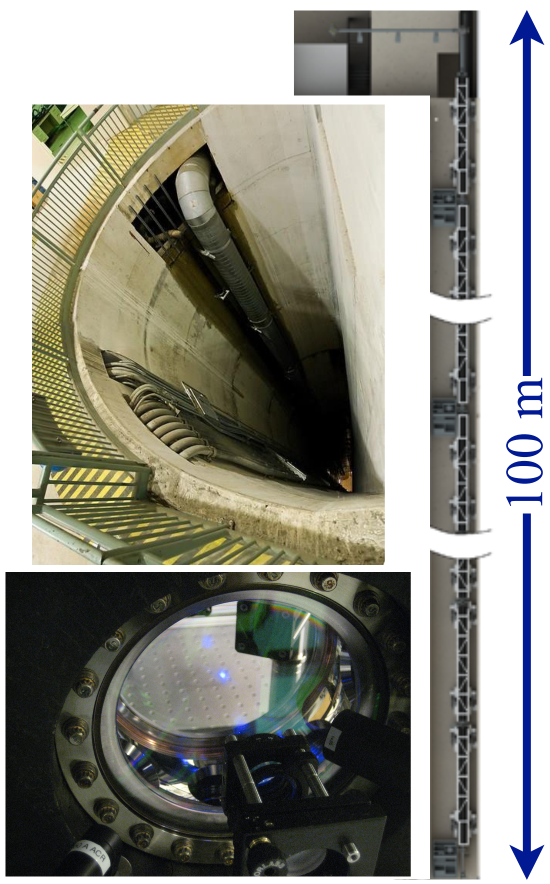
International Efforts in Gravitational Wave Detection with Atom Interferometry

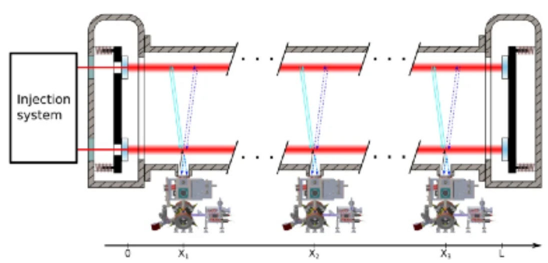
Terrestrial Detectors under construction now:

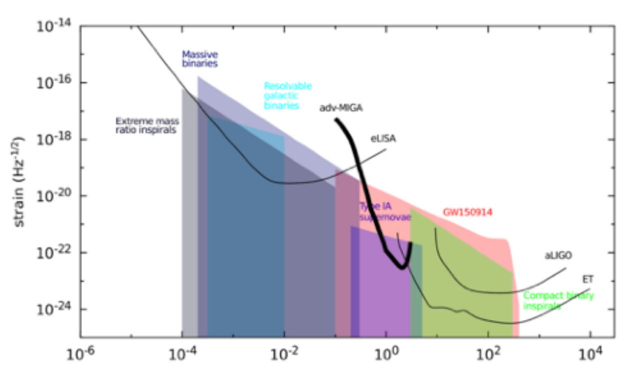
Project	Baseline Length	Number of Baselines	Orientation	Atom	Atom Optics	Location
MAGIS-100	100 m	1	Vertical	Sr	Clock AI, Bragg	USA
AION [10]	100 m	1	Vertical	Sr	Clock AI	UK
MIGA [5]	200 m	2	Horizontal	Rb	Bragg	France
ZAIGA [8]	300 m	3	Vertical	Rb, Sr	Raman, Bragg, OLC	China

MAGIS-100 (Fermilab)

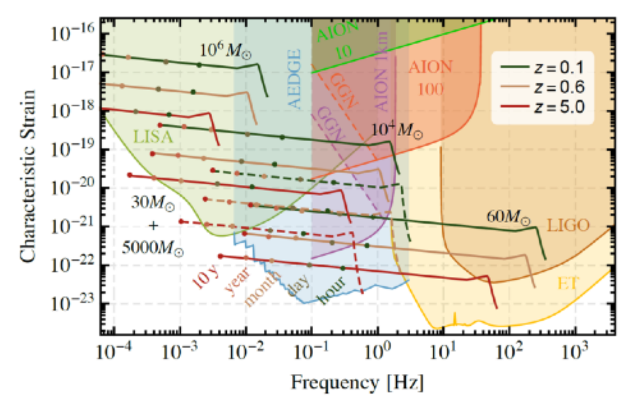


MIGA (France)

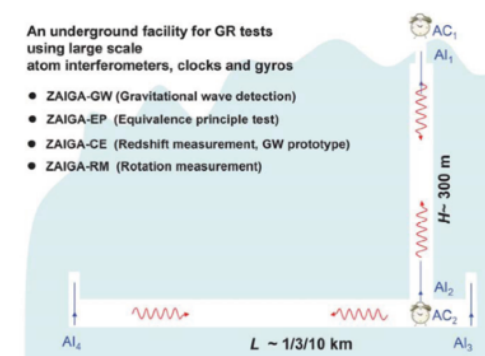


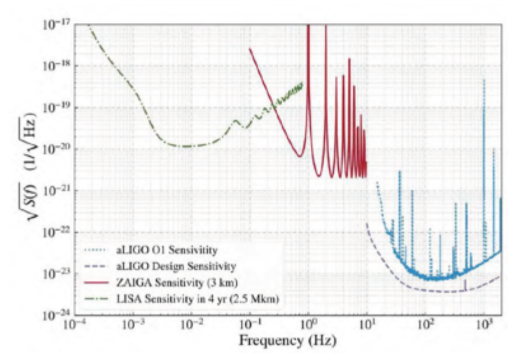


AION (UK)



ZAIGA (China)





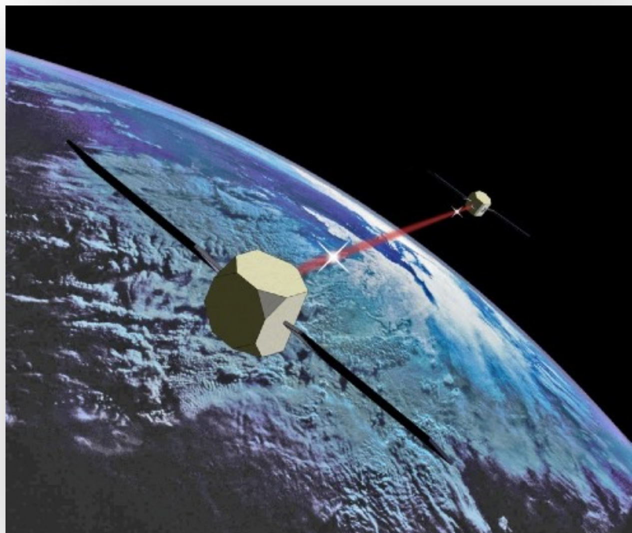
Can do ultralight dark matter detection as well

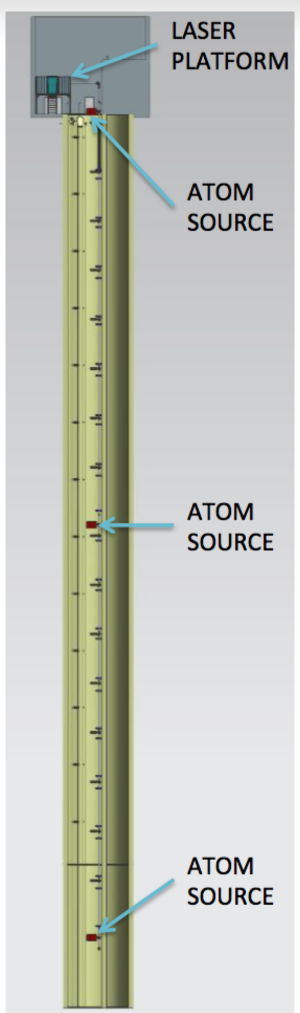
Demonstrators for ~km scale terrestrial detectors (and satellite detectors in farther future)

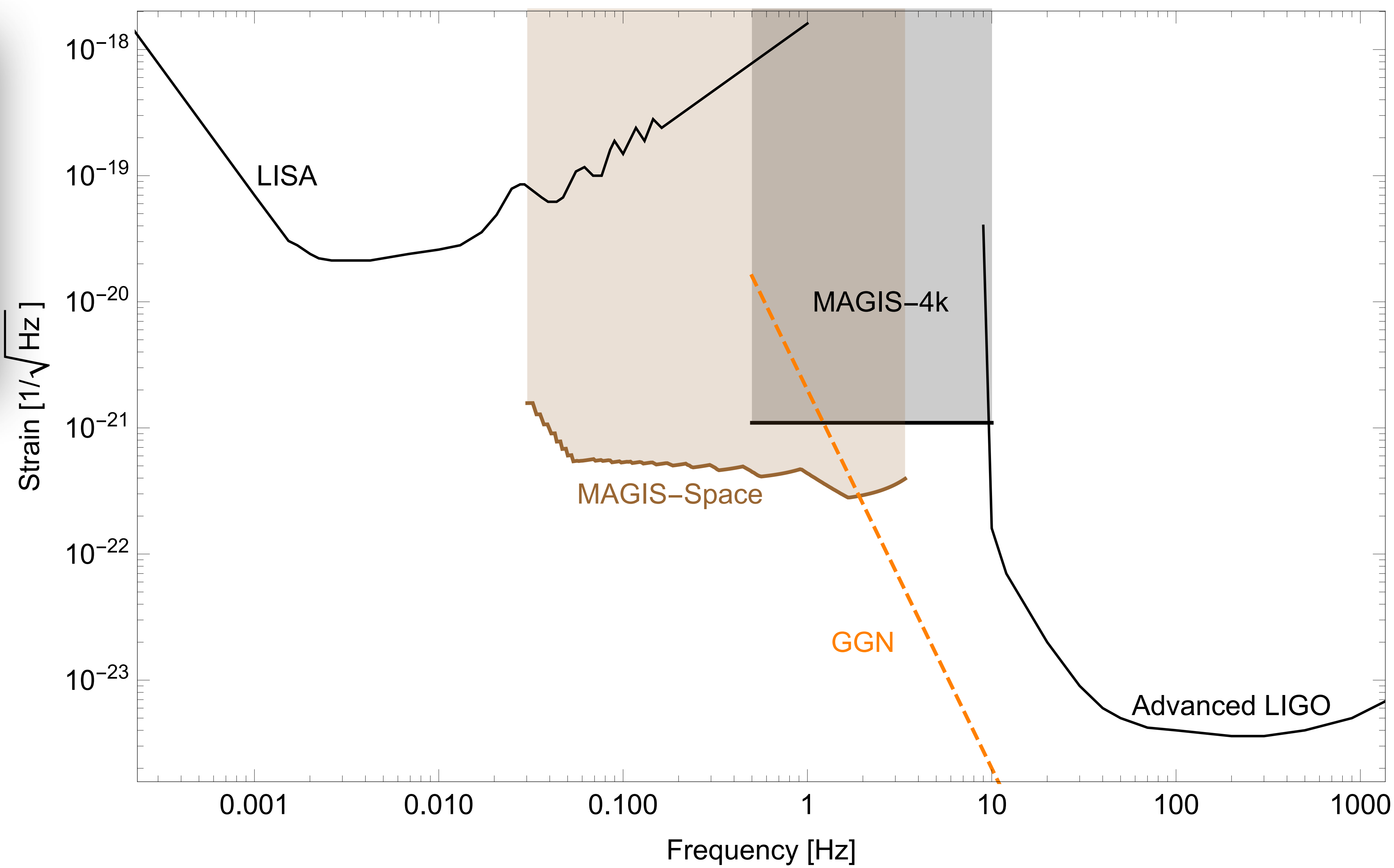
rest of talk I'll focus on science reach, use MAGIS as example

Atom Interferometry for Gravitational Waves

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







Atom Interferometry for Gravitational Waves

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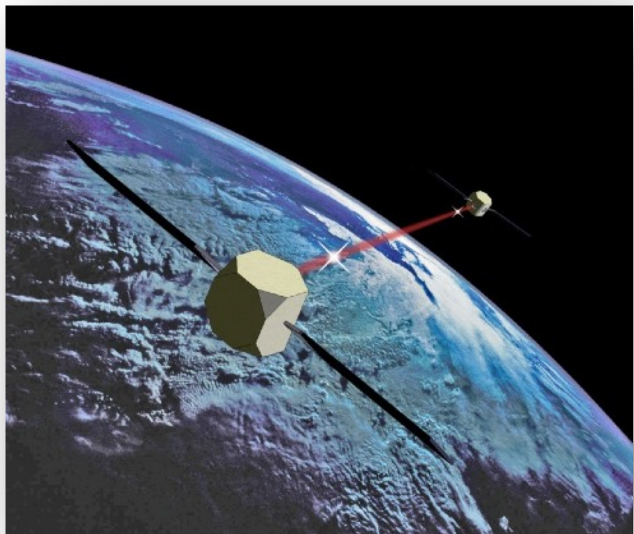
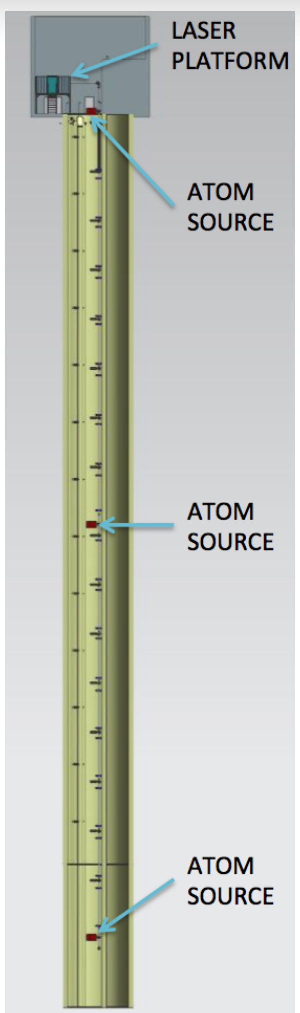
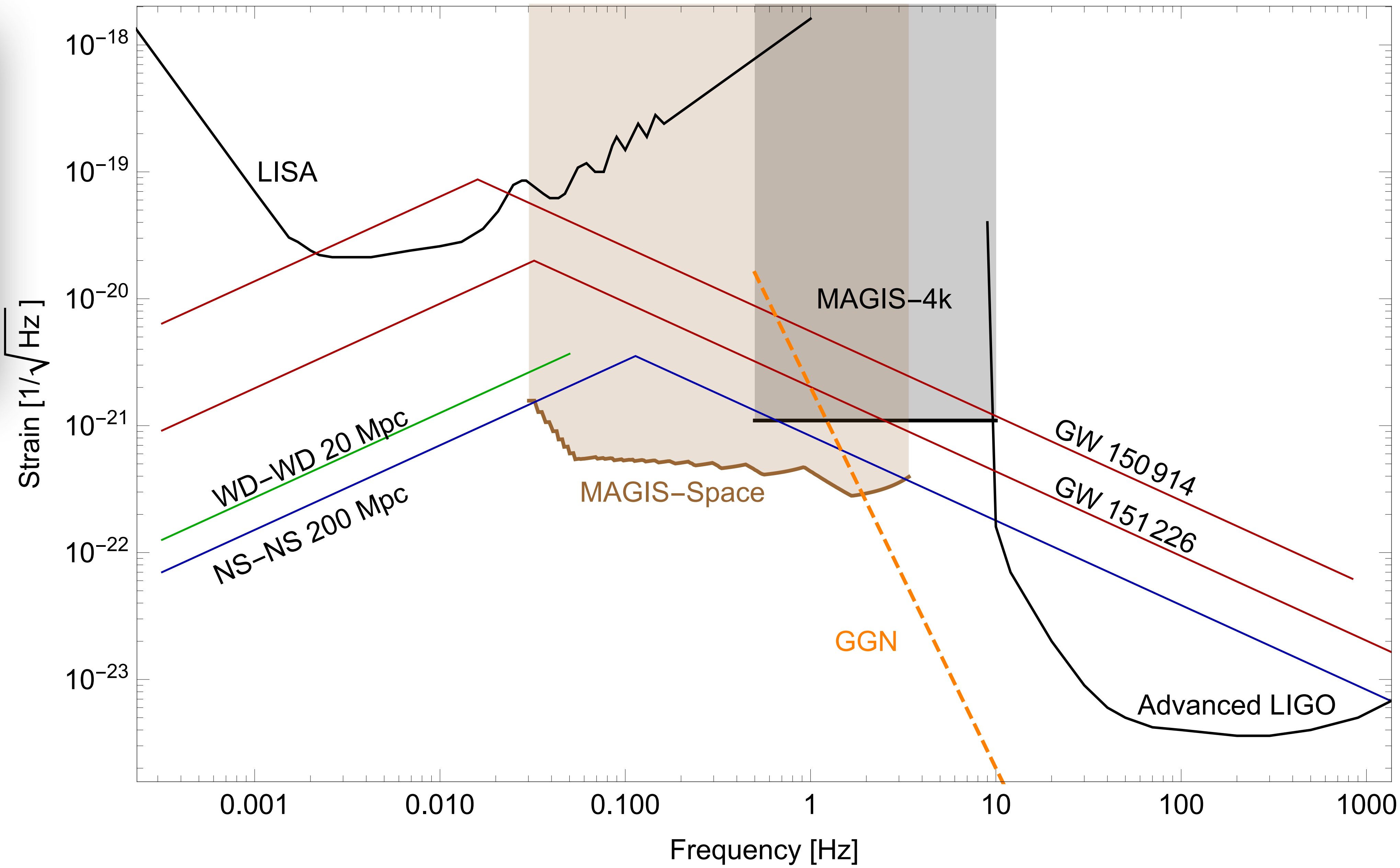




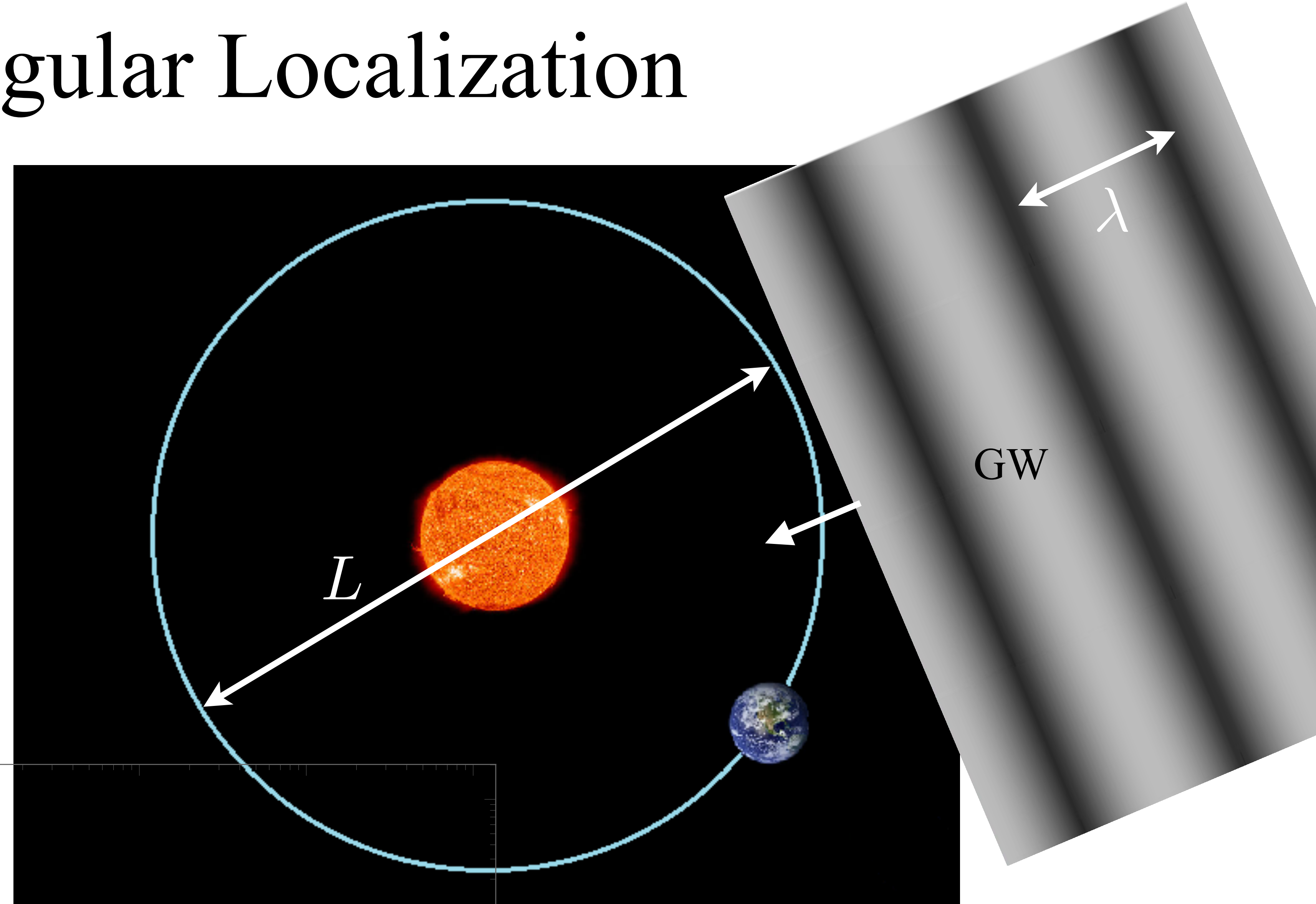


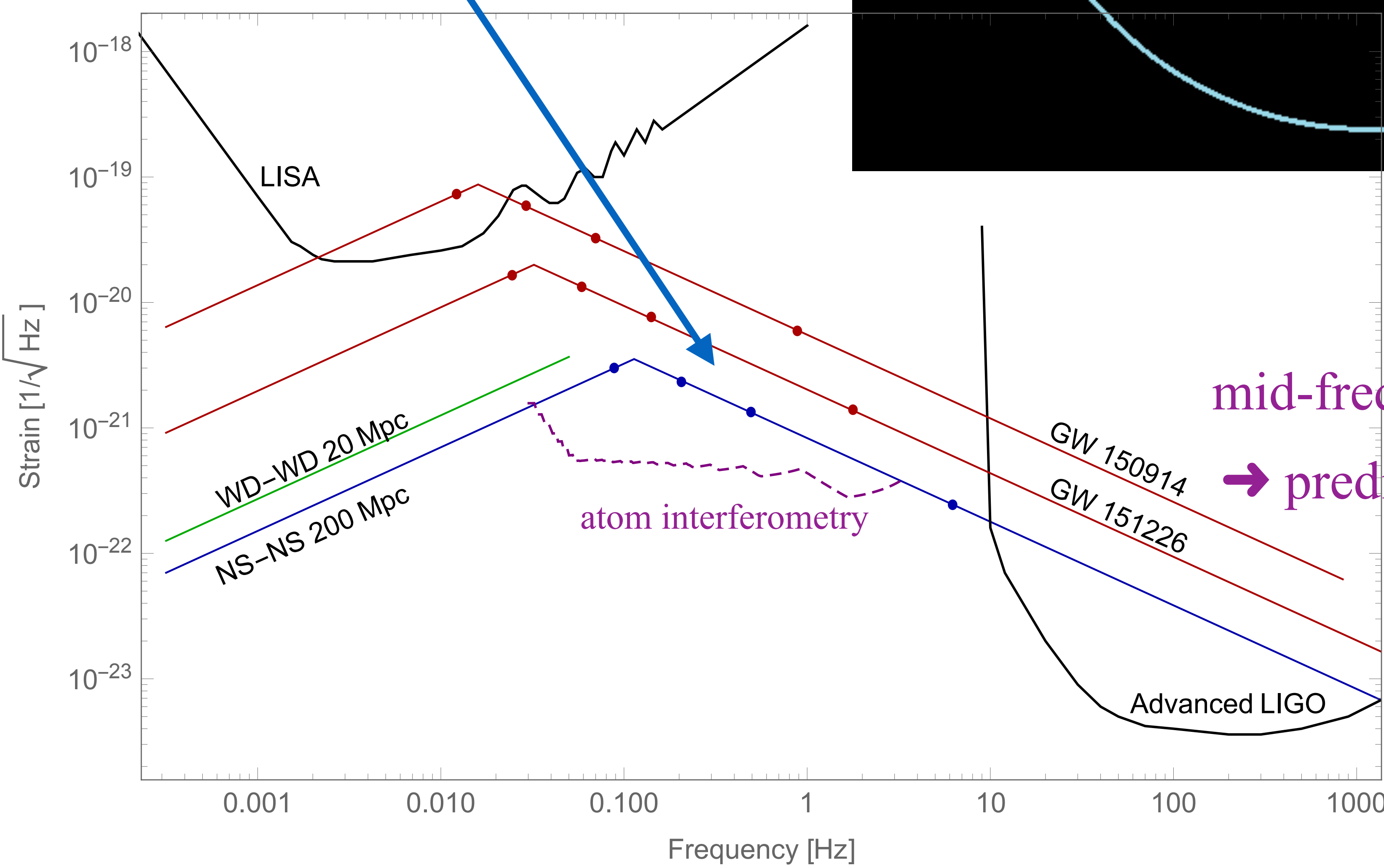
Angular Localization

phase advance across orbit dominates angular resolution

$$\Delta\theta \sim \left(\mathrm{SNR} \cdot \frac{L}{\lambda}\right)^{-1}$$

➜ highest frequencies where source lasts 6 months are best





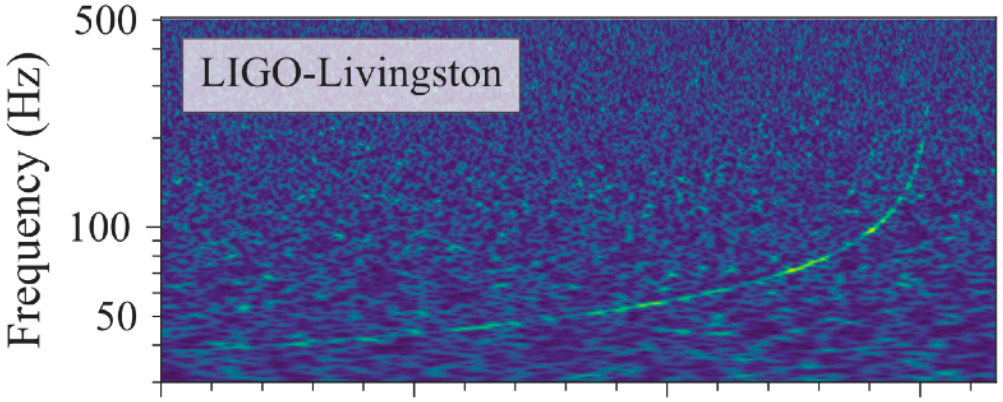
mid-frequency band ideal for angular localization

➜ predict merger time and location (sub-degree)

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

Standard Sirens

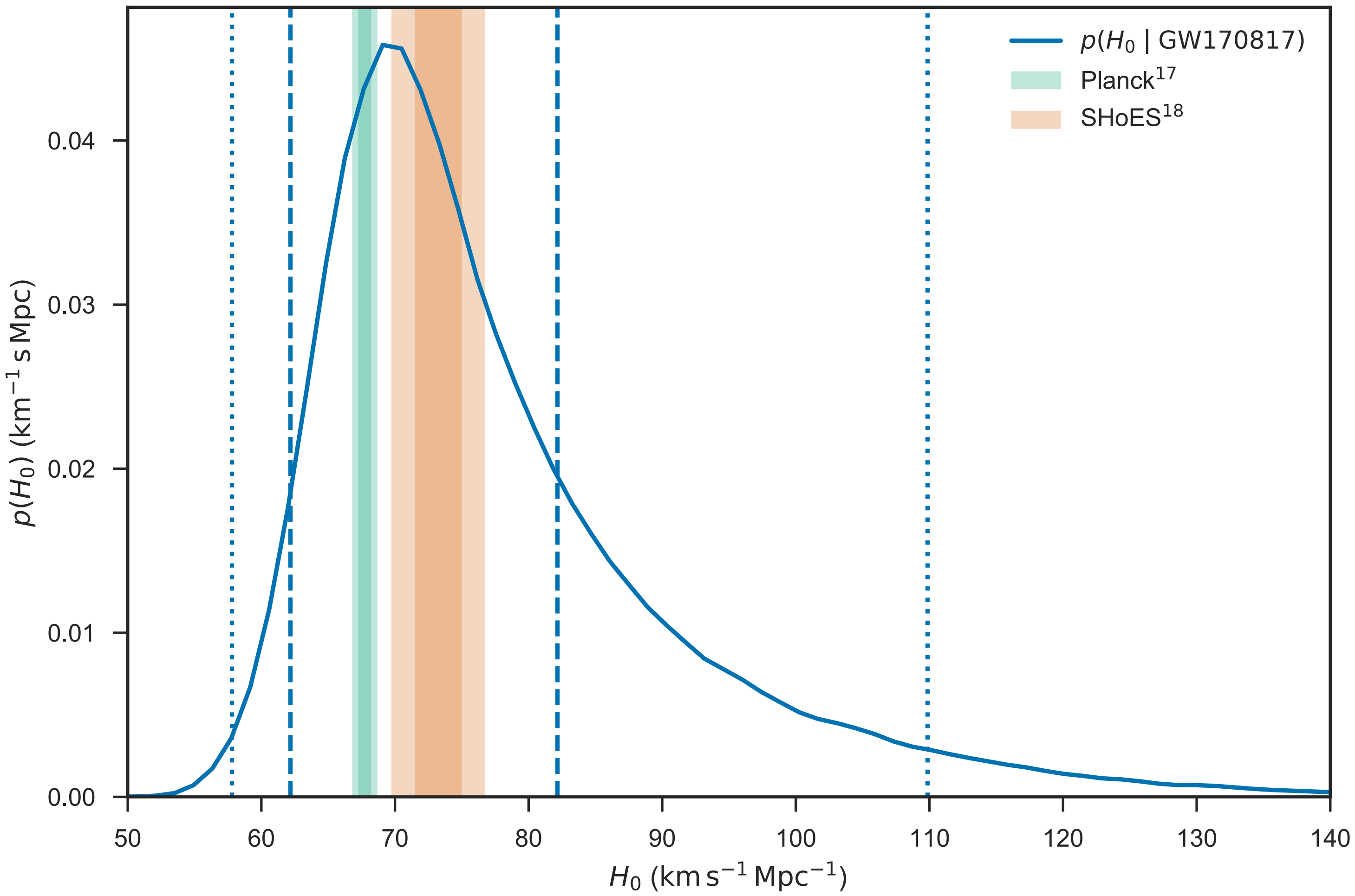
Schutz (1986)



luminosity distance measured from GW waveform,
need redshift from EM observations ➜ can do cosmology

e.g. LIGO used NS-NS merger
GW170817 ➜ measure H_0

current tension in Hubble measurements

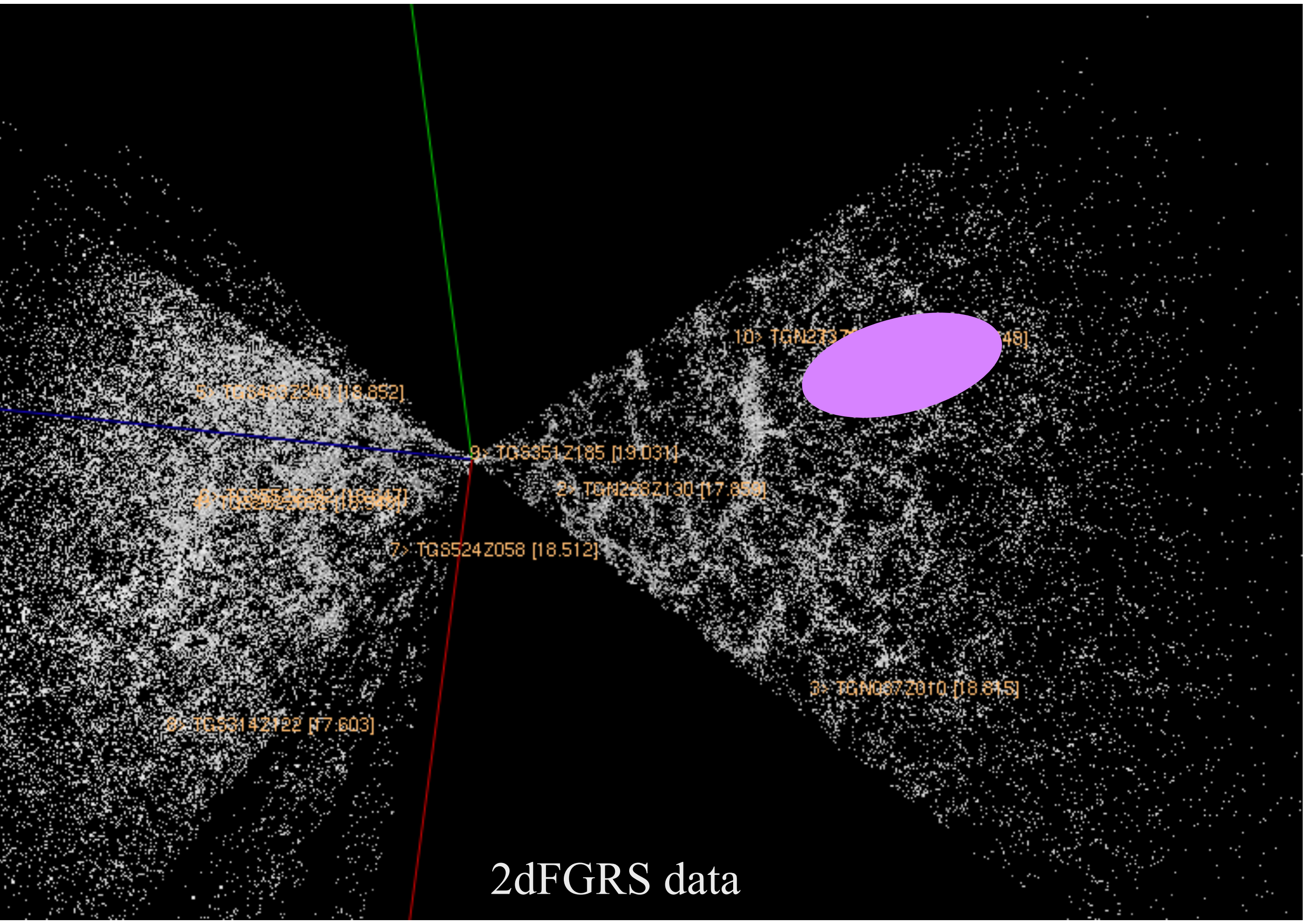


arXiv:1710.05835

independent measurement, no distance ladder needed,
ultimately limited only by measurement precision not source uncertainties
but need EM redshift

Dark Sirens

If use black hole binaries, get higher redshifts, more sirens
but how measure redshift without identified EM counterpart?



statistically match to known galaxies within error box set by GW observations

with enough events can measure distance-redshift relation precisely

attempted but challenging in LIGO's band

Chen & Holz (2016)

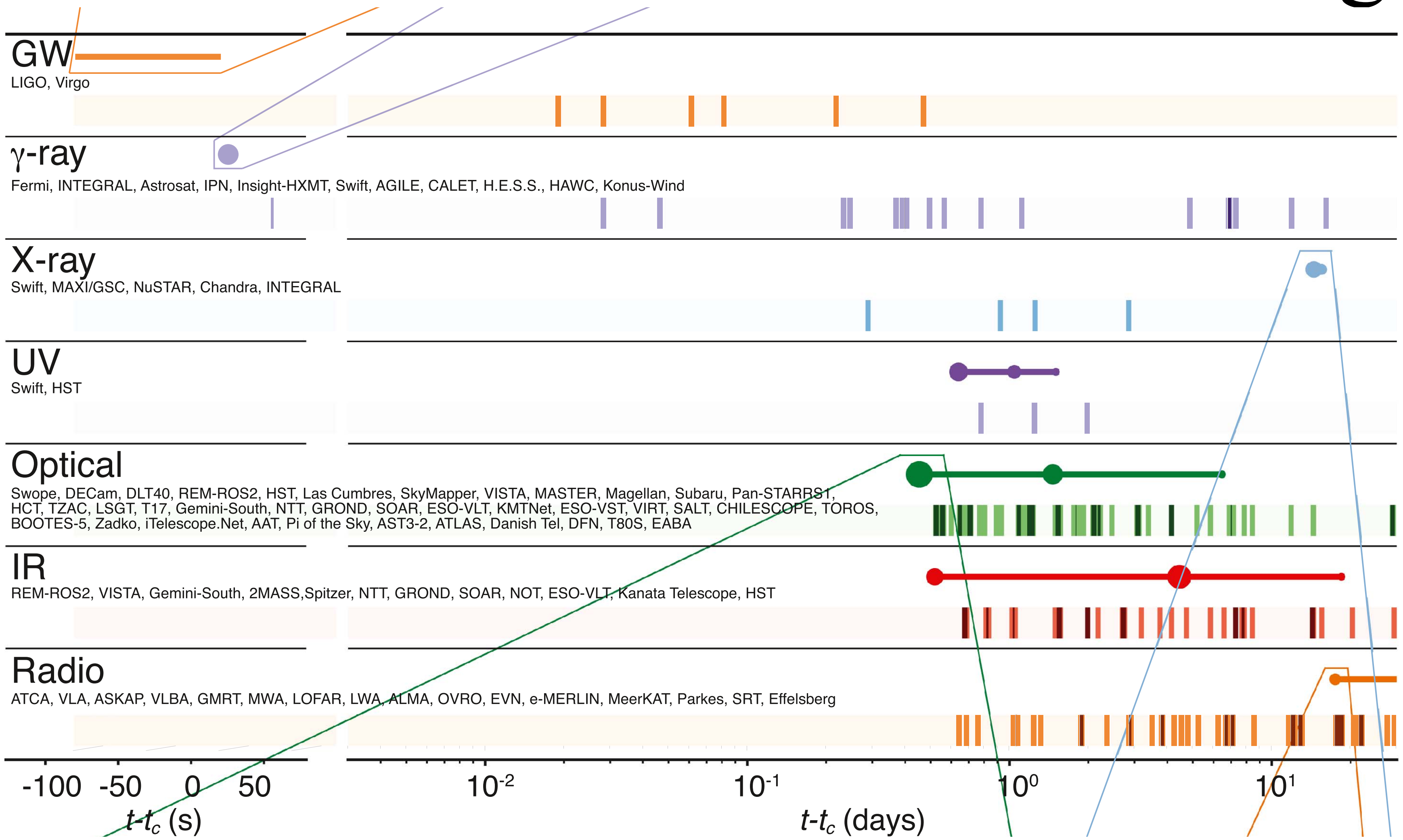
good angular resolution of mid-band greatly improves the measurement (combined with LIGO)

BH's become precision dark sirens, e.g. may allow measurement of dark energy equation of state w

(in progress)

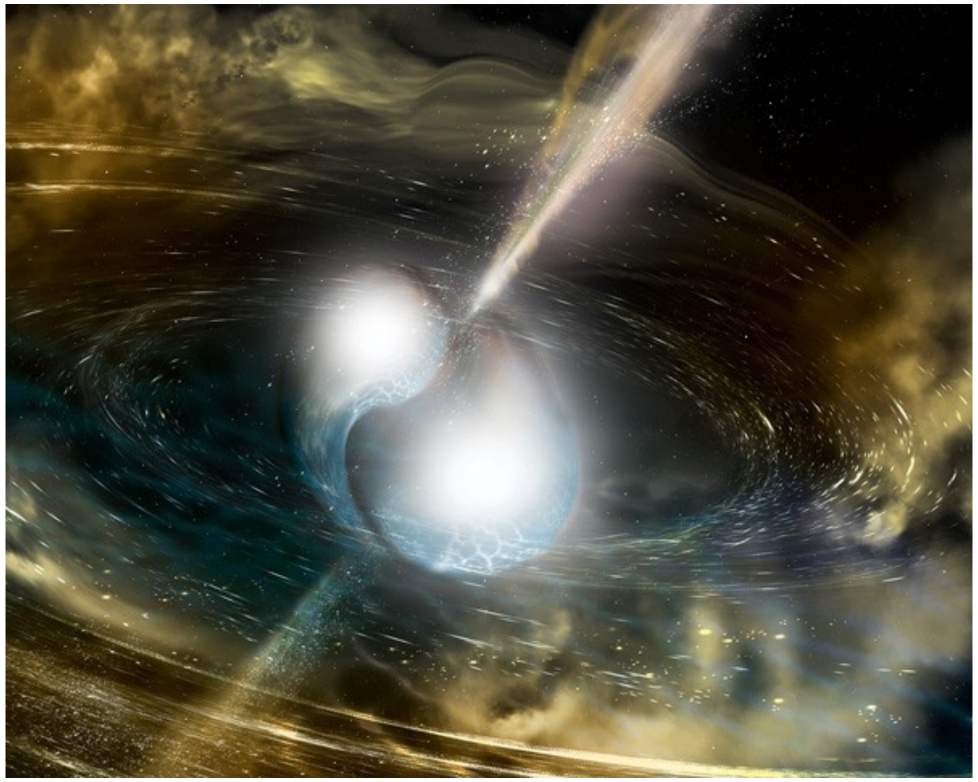
e.g. Yang et al (2110.09967)

Neutron Star Mergers



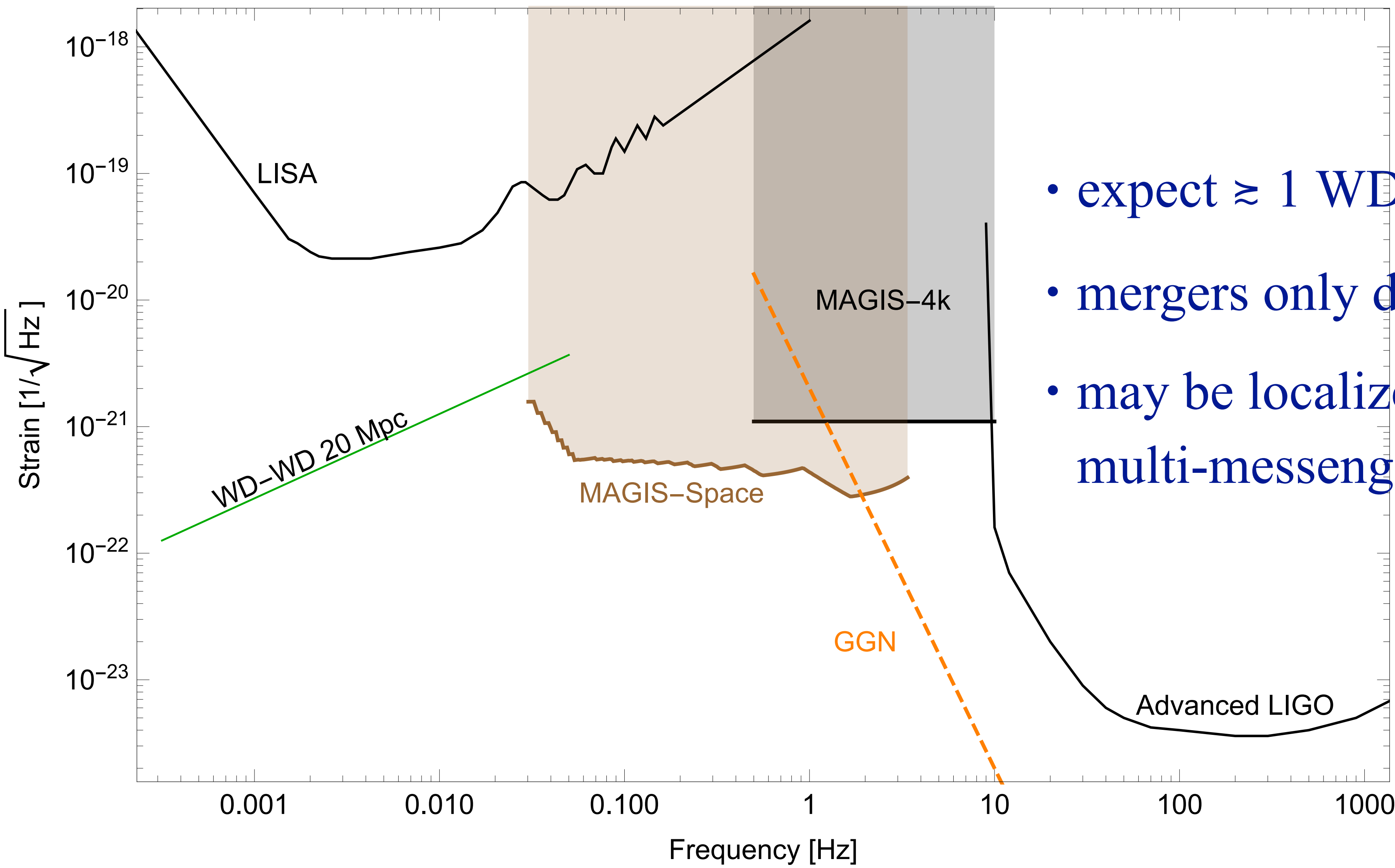
Ap.J.Lett. **848** (2017)

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



- expect ≳ 1 WD merger per year within 20 Mpc
- 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
- improve calibration of standard candles?

Mid-band GW Science

complementary to LIGO (and future LISA), combining gives much more information

Observing with MAGIS 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 more we haven’t thought of yet!

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

Atomic Clocks and Gravitational Waves at ~ 1-10 μHz

(PRELIMINARY)

with

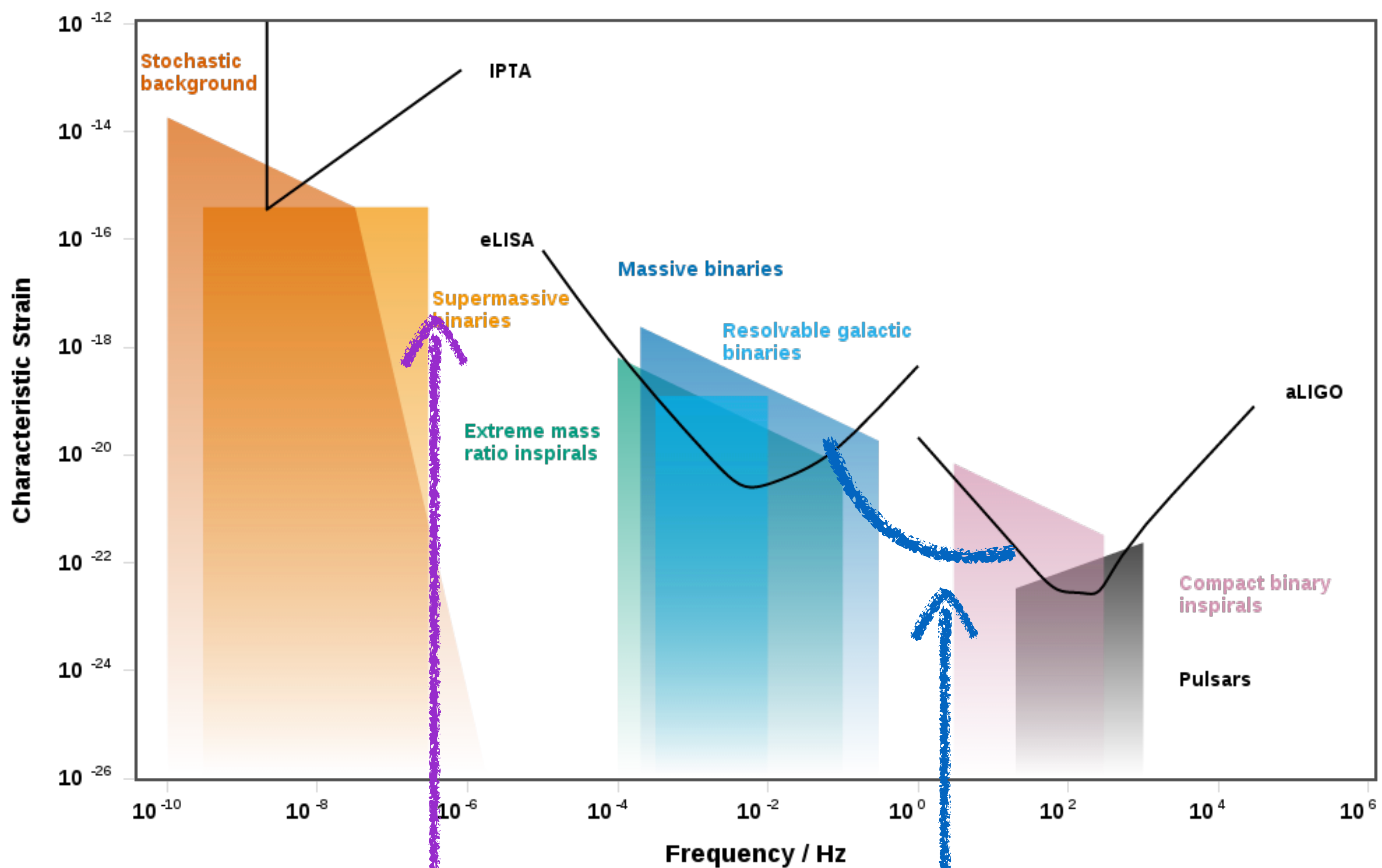
Michael Fedderke

Surjeet Rajendran

to appear soon

Gravitational Spectrum

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



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

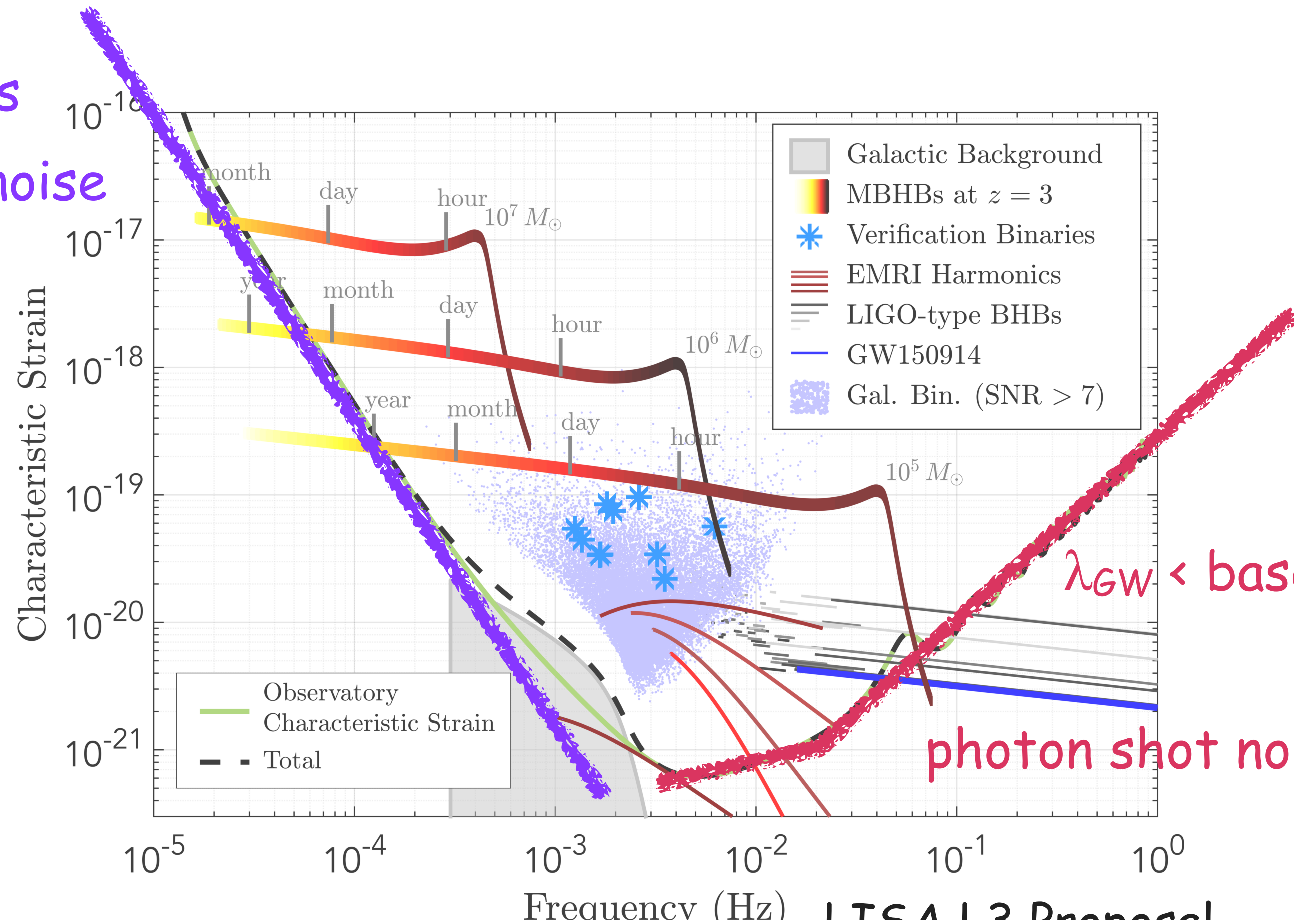
atomic interferometry
(MAGIS, clocks, MIGA, AION...)

Why the “μHz Gap”?

Why doesn’t LISA reach lower frequencies?

proof mass
acceleration noise

rises at low
frequency

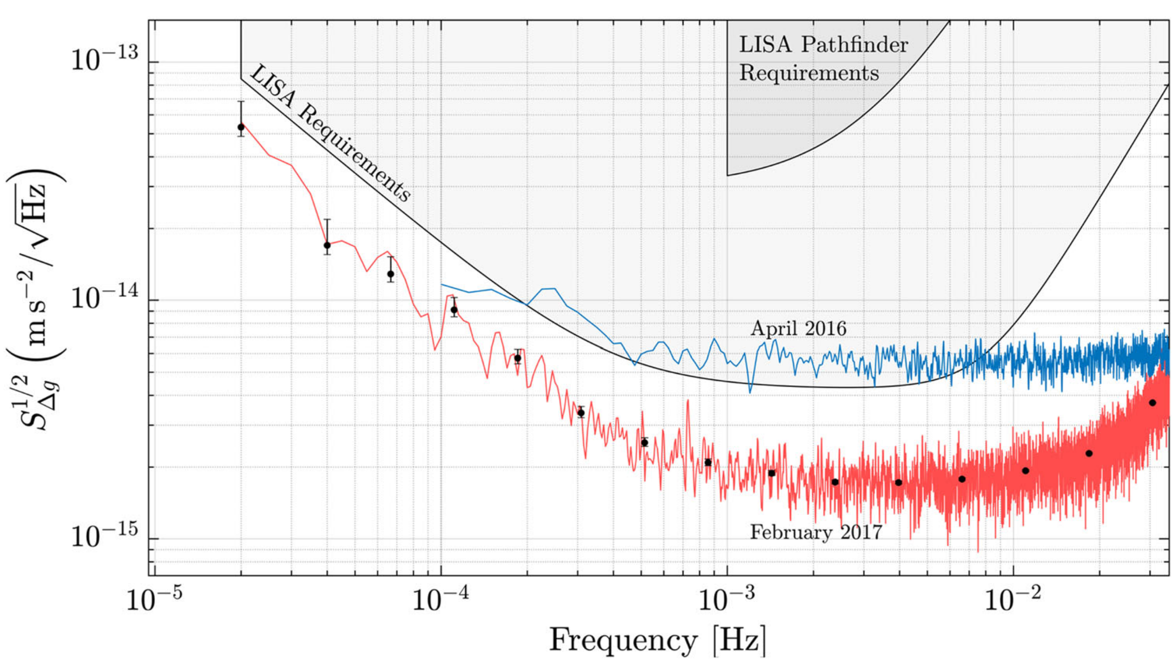


λ_{GW} < baseline

photon shot noise

LISA L3 Proposal

measured:



LISA Pathfinder PRL (2018)

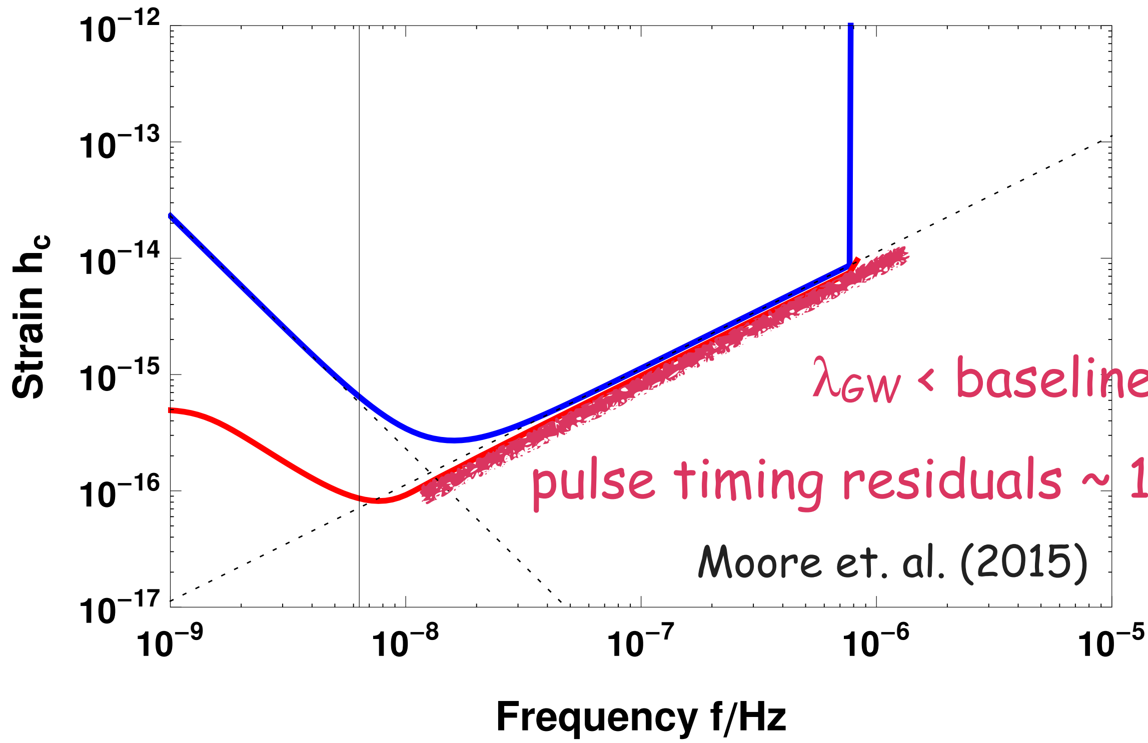
How could you reach lower frequencies?

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

Astrophysical Proof Masses

Why doesn't Pulsar Timing reach higher frequencies?

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



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

want: shorter baseline for good SNR of pulses, human-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?

Want much bigger than a satellite so small forces don't disturb

Want smaller than the Earth so no atmosphere or plate tectonics:

can we use asteroids?

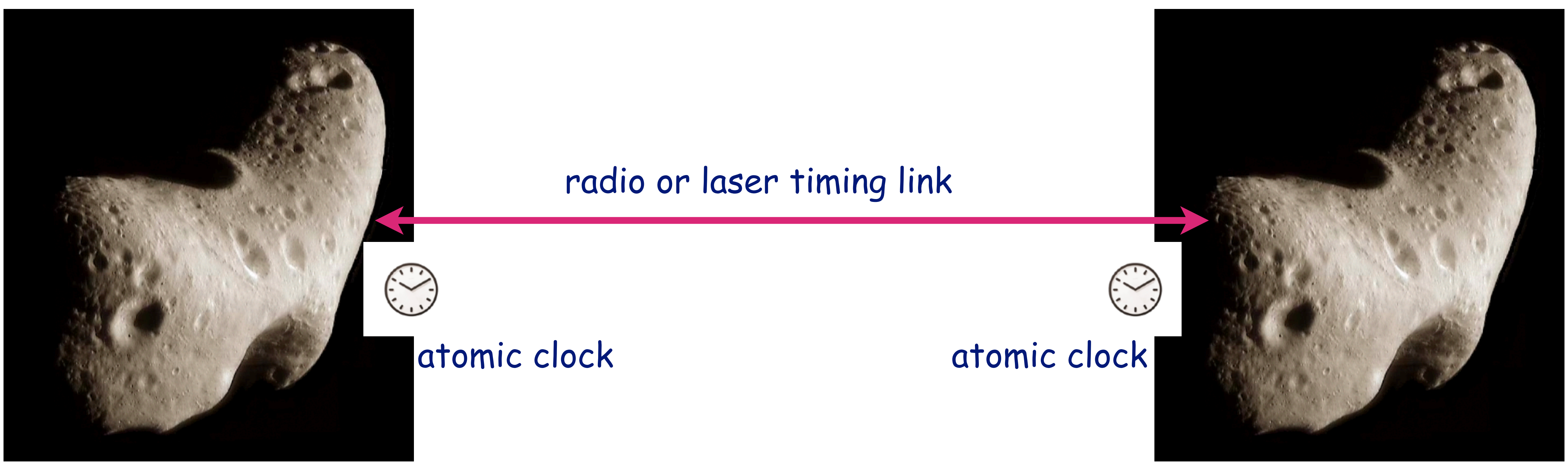
Will evaluate asteroids as inertial proof masses

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

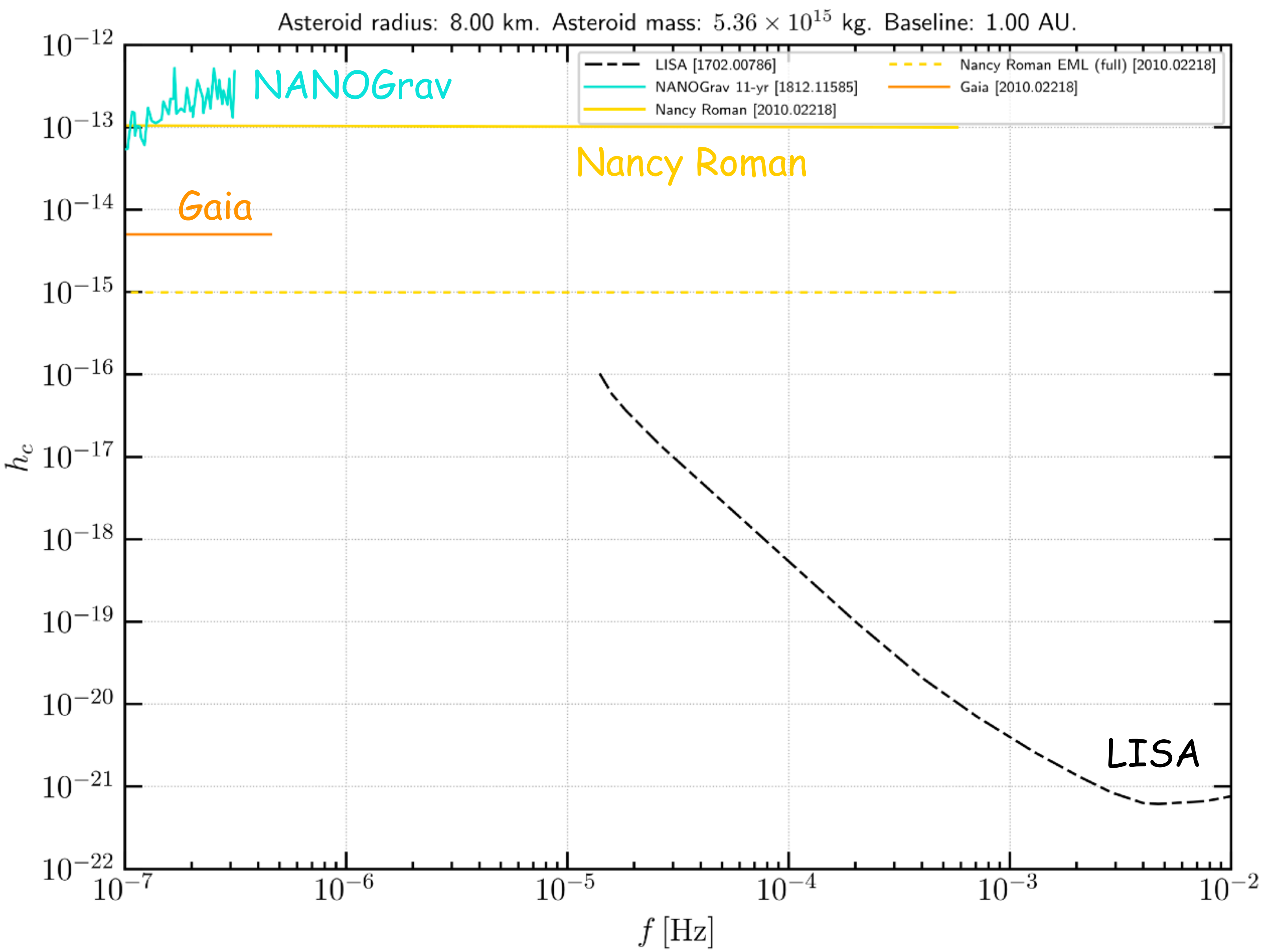
even "driven" rovers, collected samples…

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

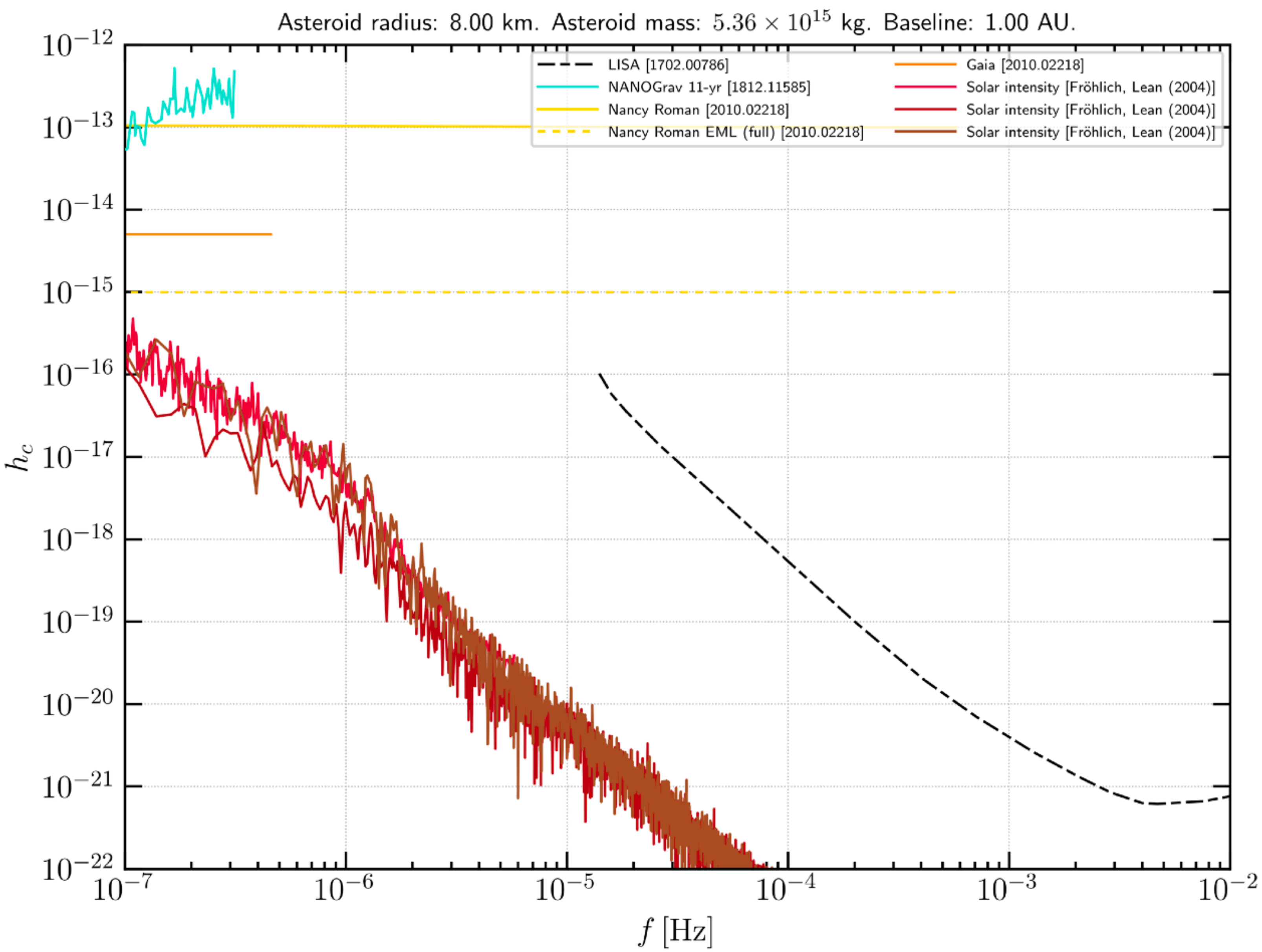
Unexplored GW Band



Solar Intensity Acceleration Noise

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

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



strain ASD:

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

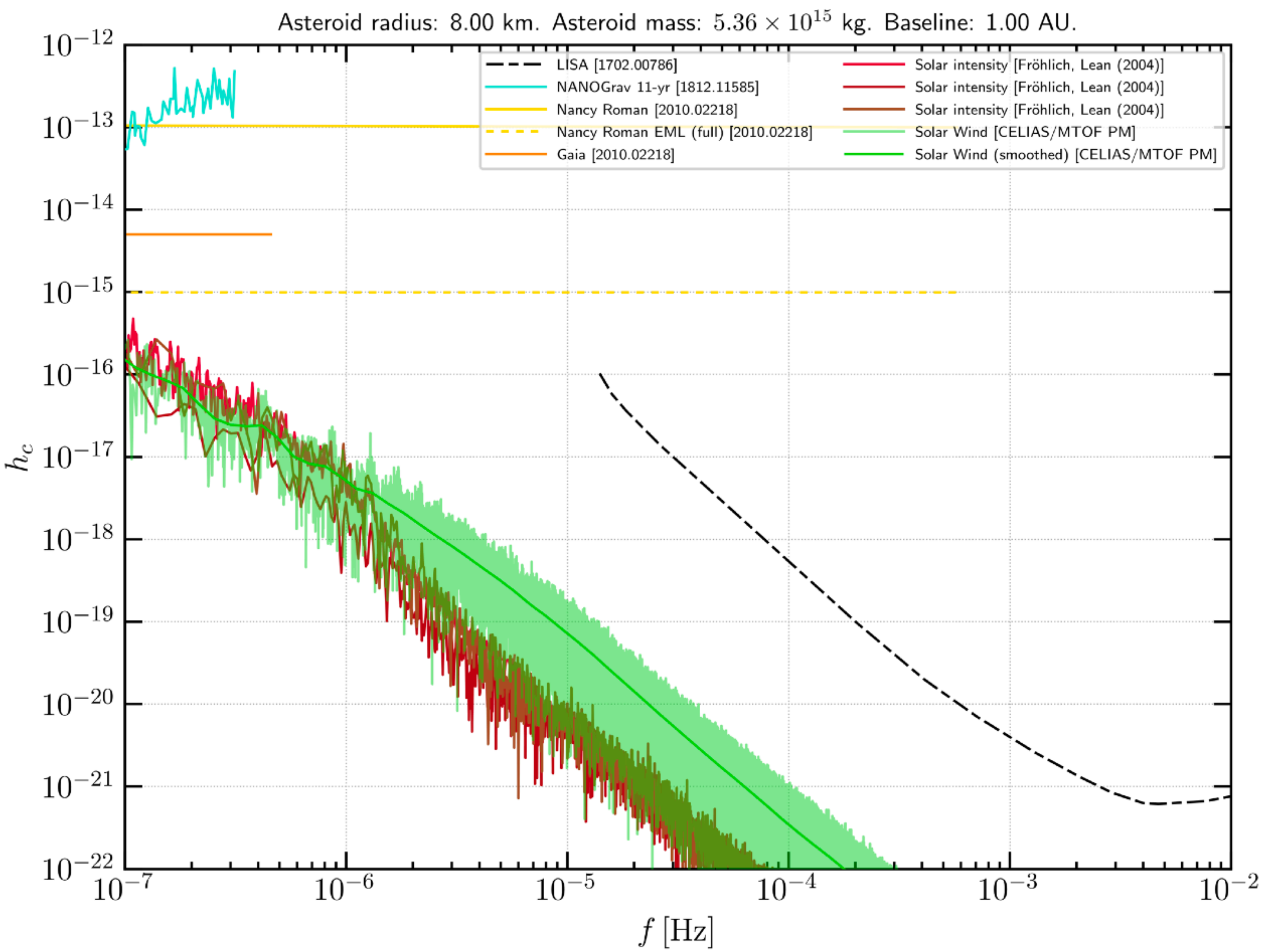
measured solar intensity PSD

Fröhlich & Lean (2004)

diameters > 1 km give sufficient noise suppression

Solar Wind Acceleration Noise

Measured solar wind fluctuations, applied to example asteroid



strain ASD:

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

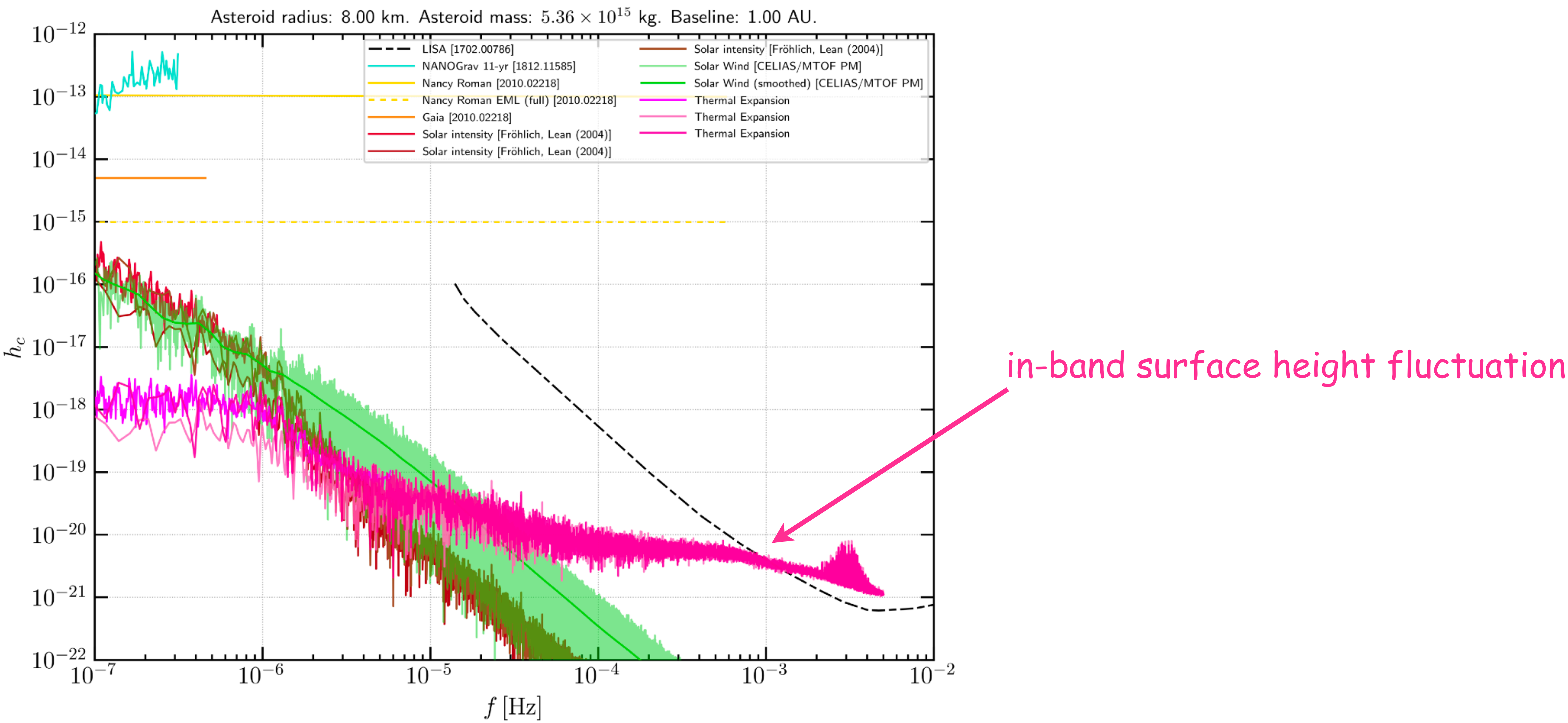
measured solar wind PSD

CELIAS, MTOF monitor on SOHO satellite

$$\Omega = n_p v_p^2$$

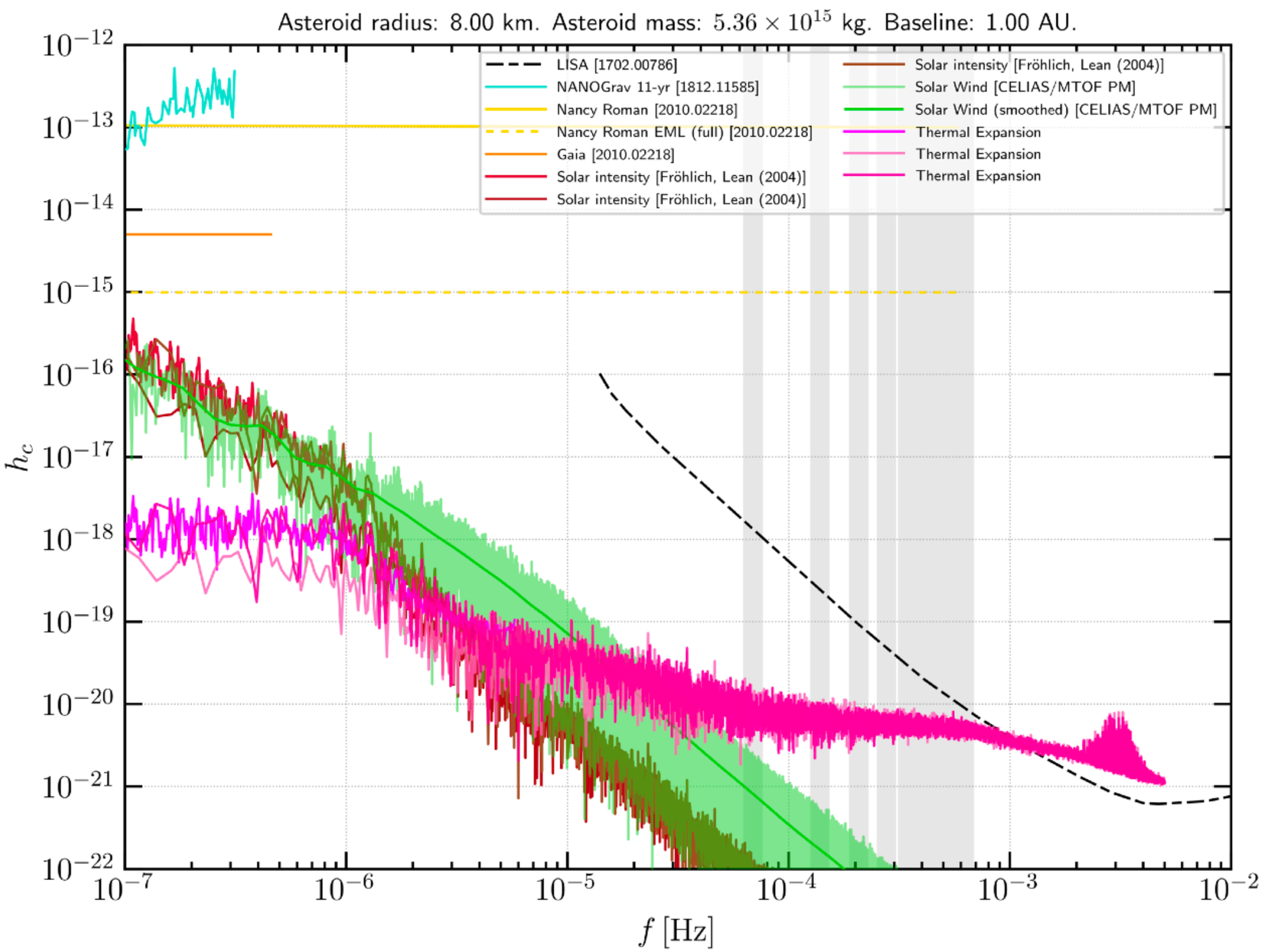
Thermal Noise

Solar intensity fluctuations cause variable heating ➜ thermal expansion noise



Rotation Noise

Asteroid rotation periods generally ~ few hours



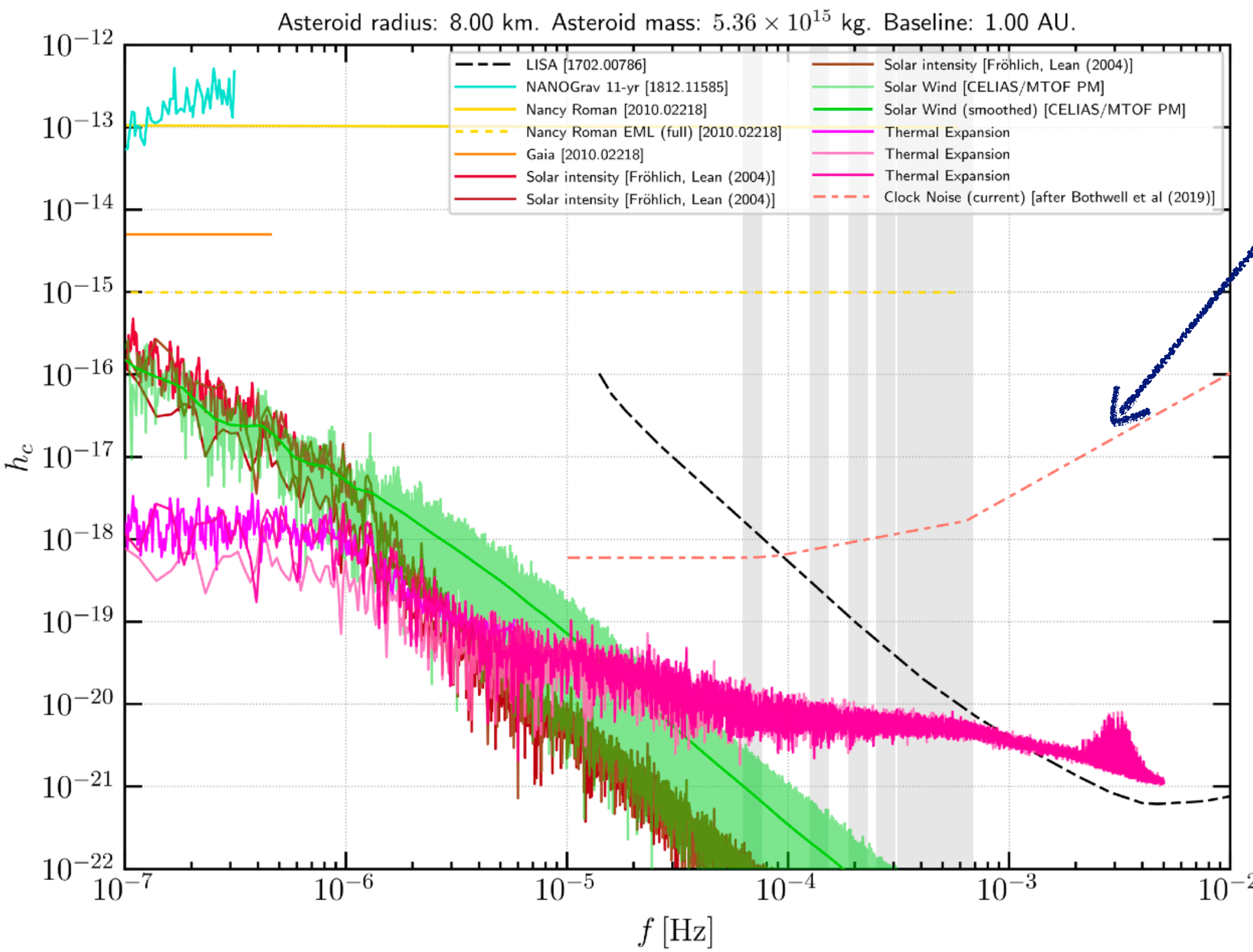
removes higher frequency bands

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

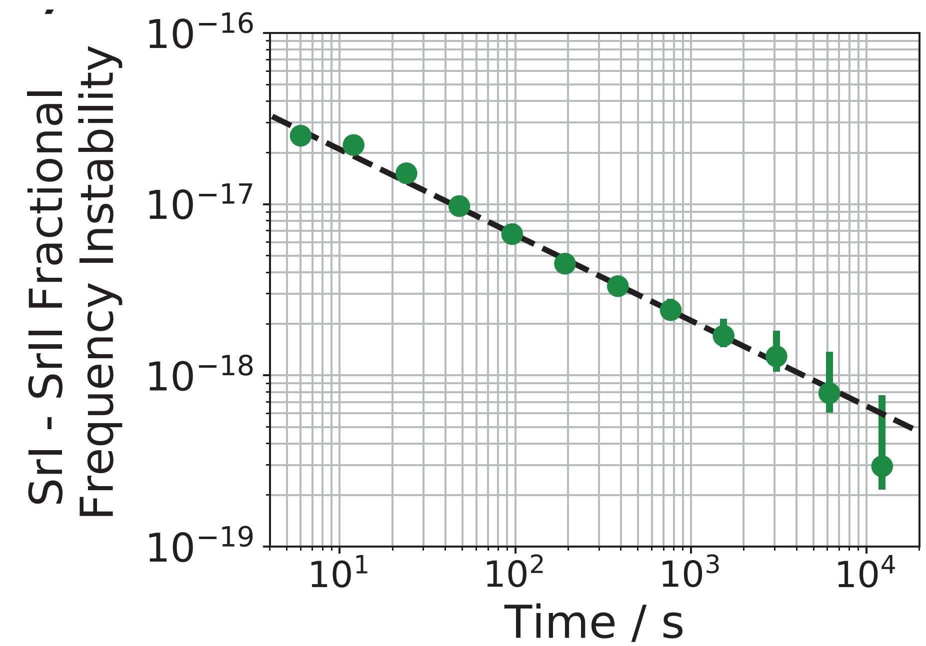
asteroid as inertial proof mass allows significant improvement at low frequencies

Clock Noise

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



translated current atomic clock



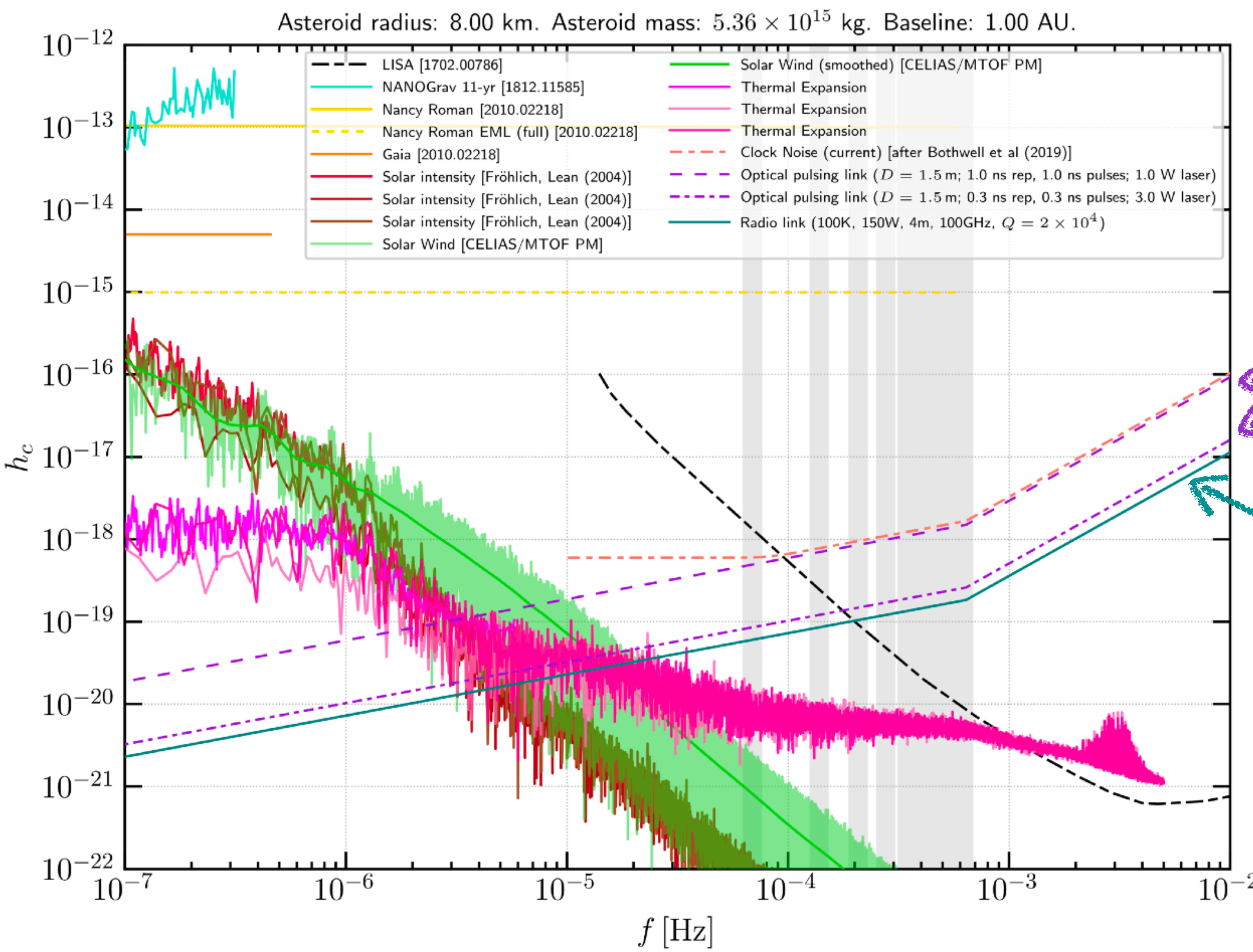
Bothwell et. al. (2019)

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



laser pulsing

radio interferometry

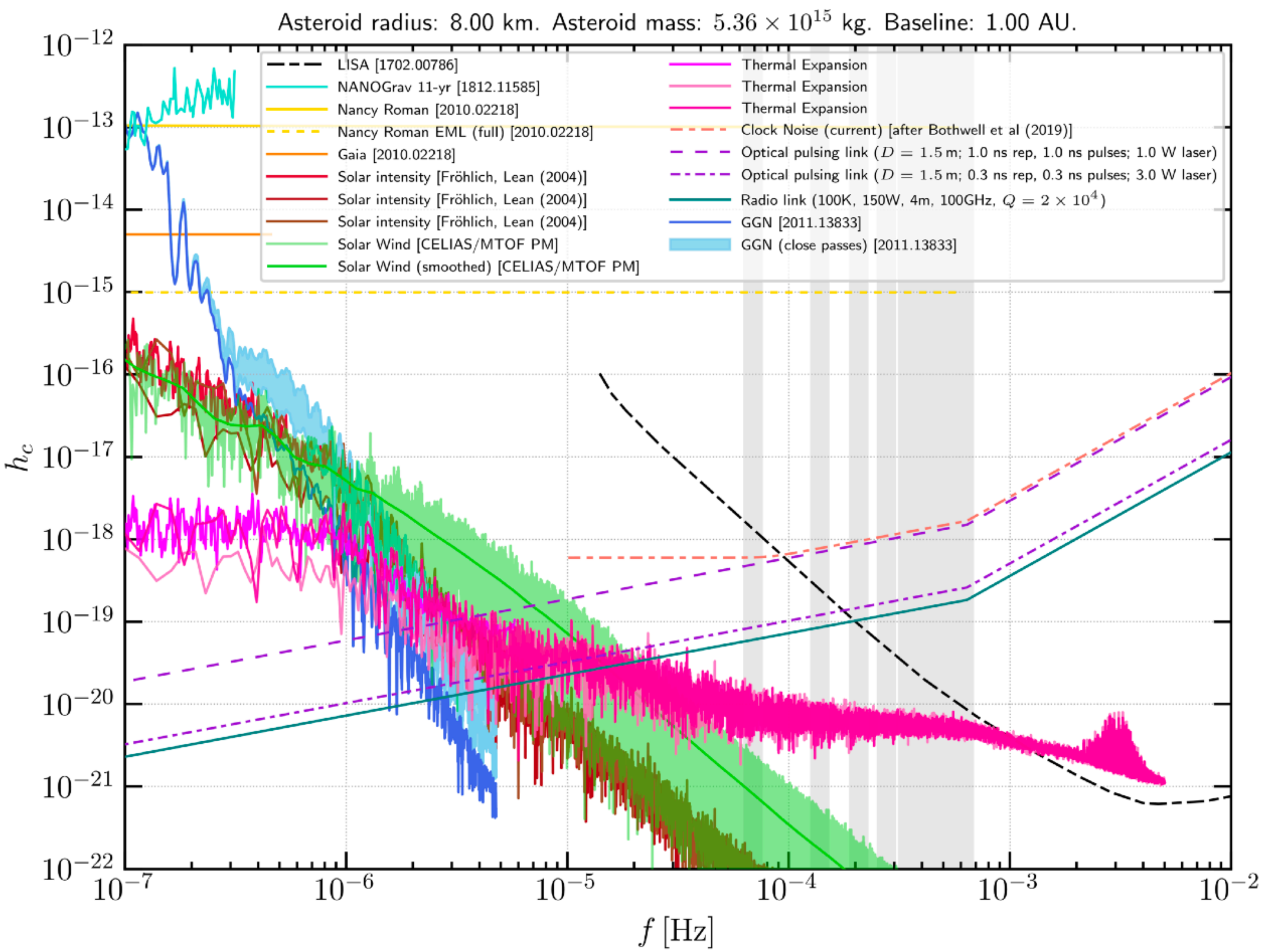
asteroids have significant, uncontrollable relative motion

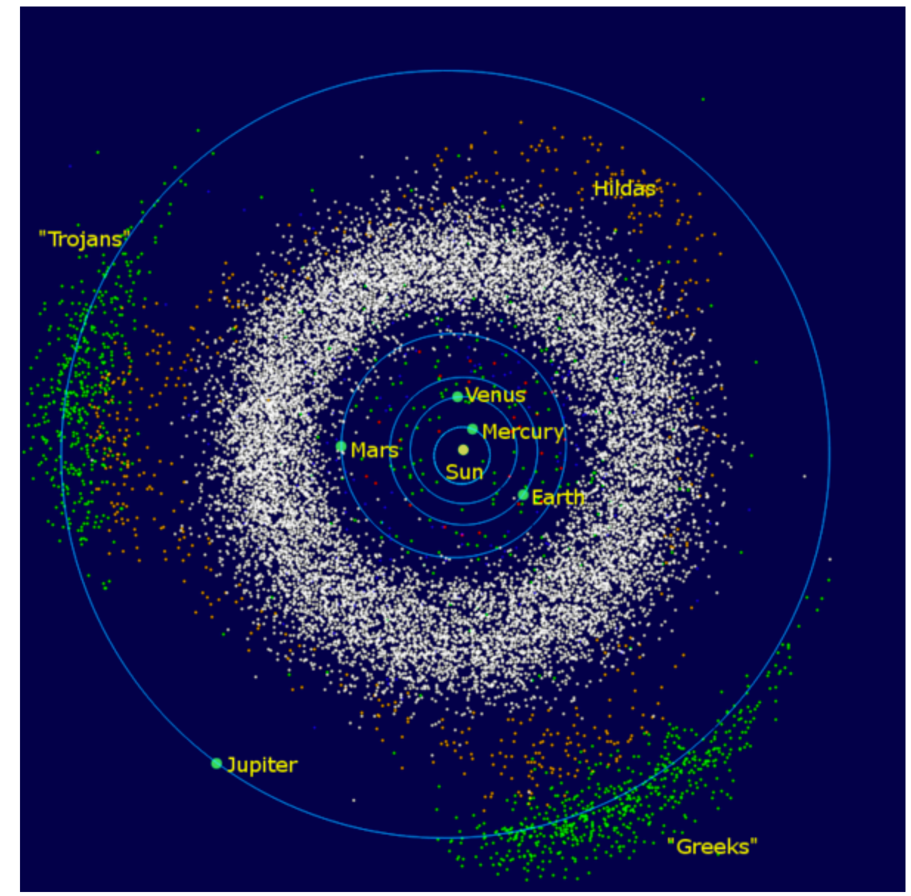
possibly allows a link system with significantly reduced technical complications relative to optical interferometry

Asteroid Gravity Gradient Noise

predominantly around orbital period (of detector) ~ few years

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





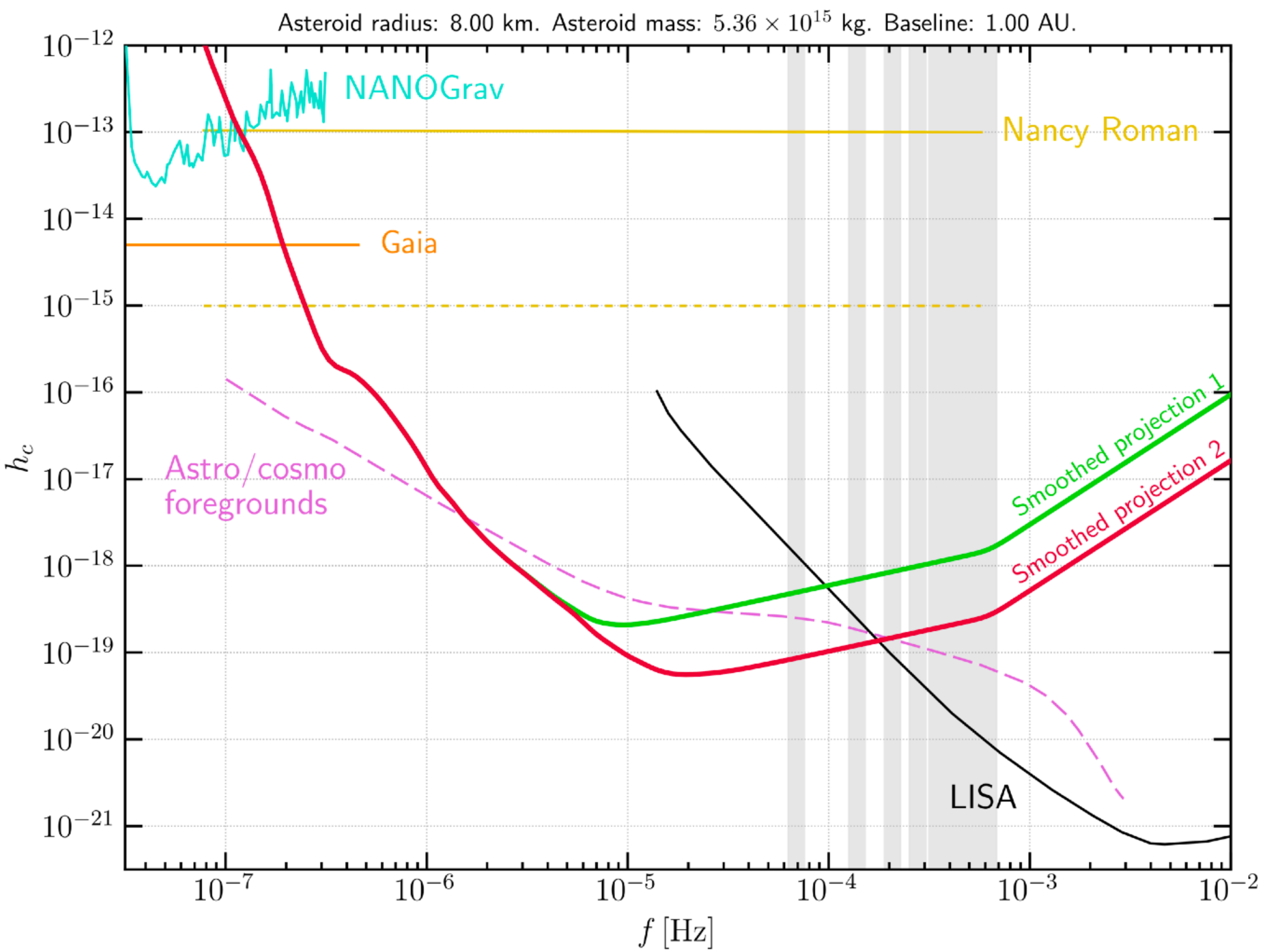
dedicated simulation using NASA JPL asteroid catalog, supplemented with estimate for higher frequency "close pass" noise of unmodeled asteroids using e.g. lunar crater data

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

another "gap" in gravitational spectrum?

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!

Summary

Atom interferometer-based GW detectors could observe the “mid-band” ~ 1 Hz

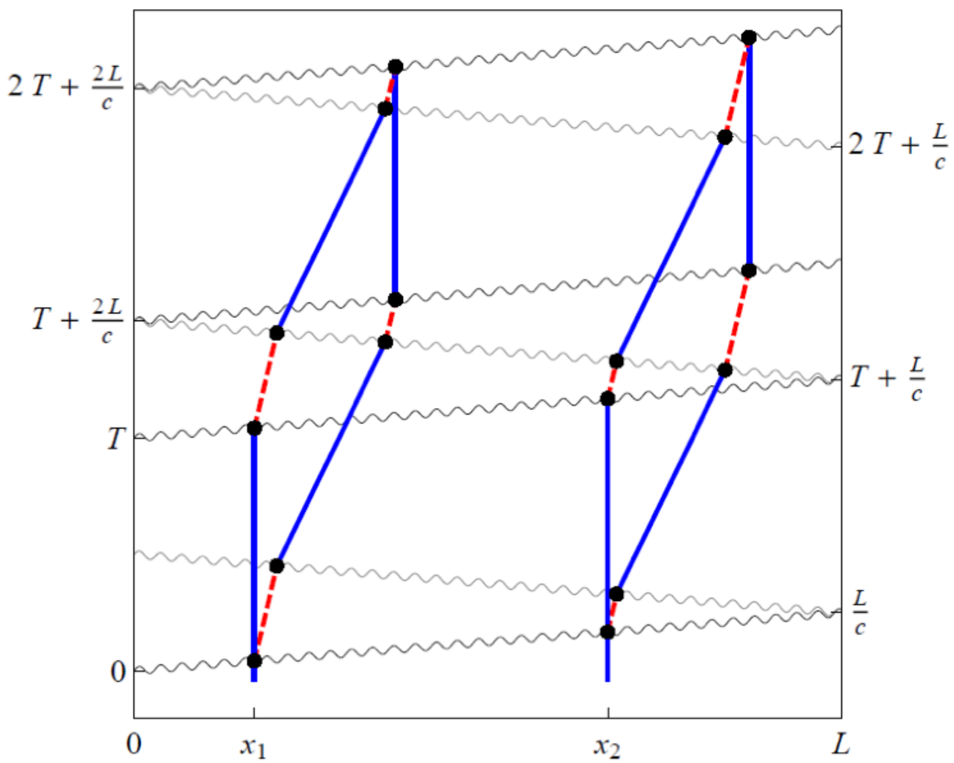
- 100 m class demonstrators under construction now (e.g. MAGIS-100 at Fermilab)
- Science case for this band is broad (and expanding)

Asteroids (with atomic clocks) may be good proof masses for GW’s in μHz band

- no existing methods can access this band
- warrants further study

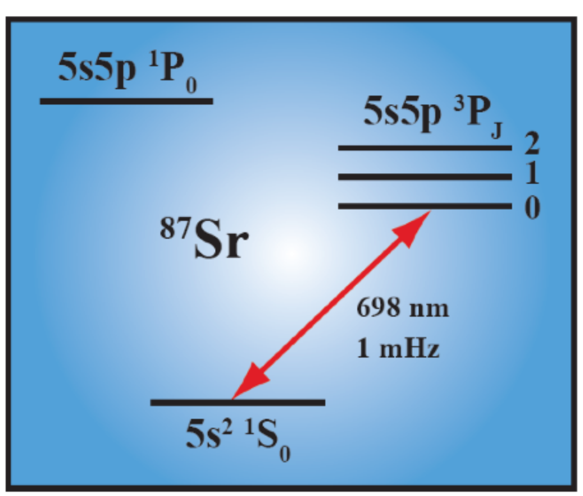
Backup Slides

Mid-band Atomic Gravitational wave Interferometric Sensor (MAGIS)



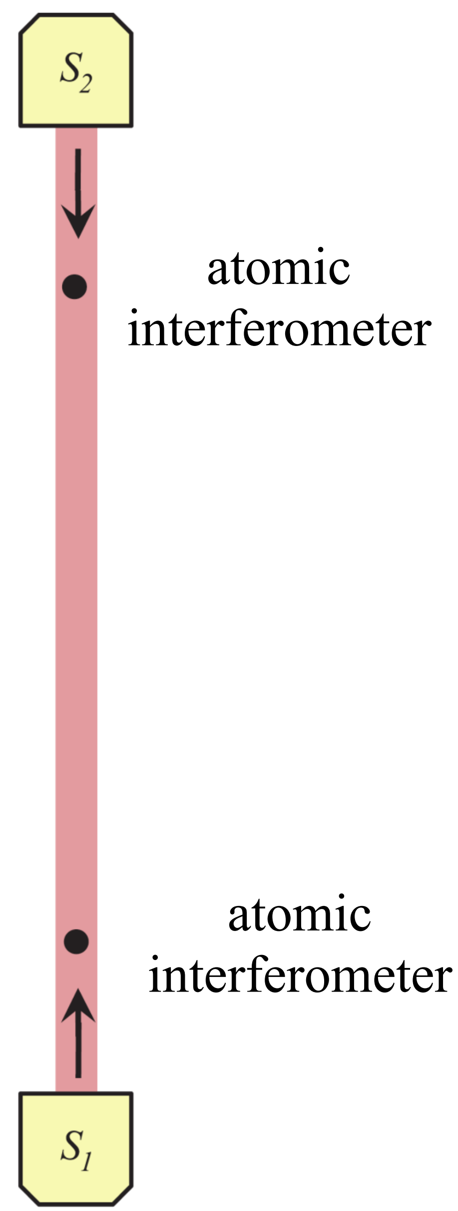
run as hybrid clock/accelerometer

PWG, Hogan, Kasevich, Rajendran PRL **110** (2013)



Clock transition in candidate atom ^{87}Sr

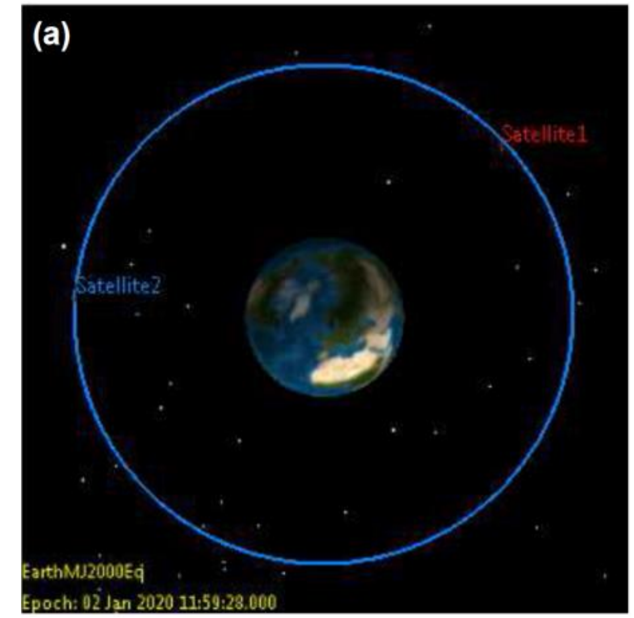
gravitational wave detection:



- based on atomic clock technology
- atoms measure light travel time
- accelerometer ➜ can use atoms as good inertial proof masses
- differential measurement allows reduction of many noise sources
- e.g. seismic noise removed ➜ observe frequencies below LIGO

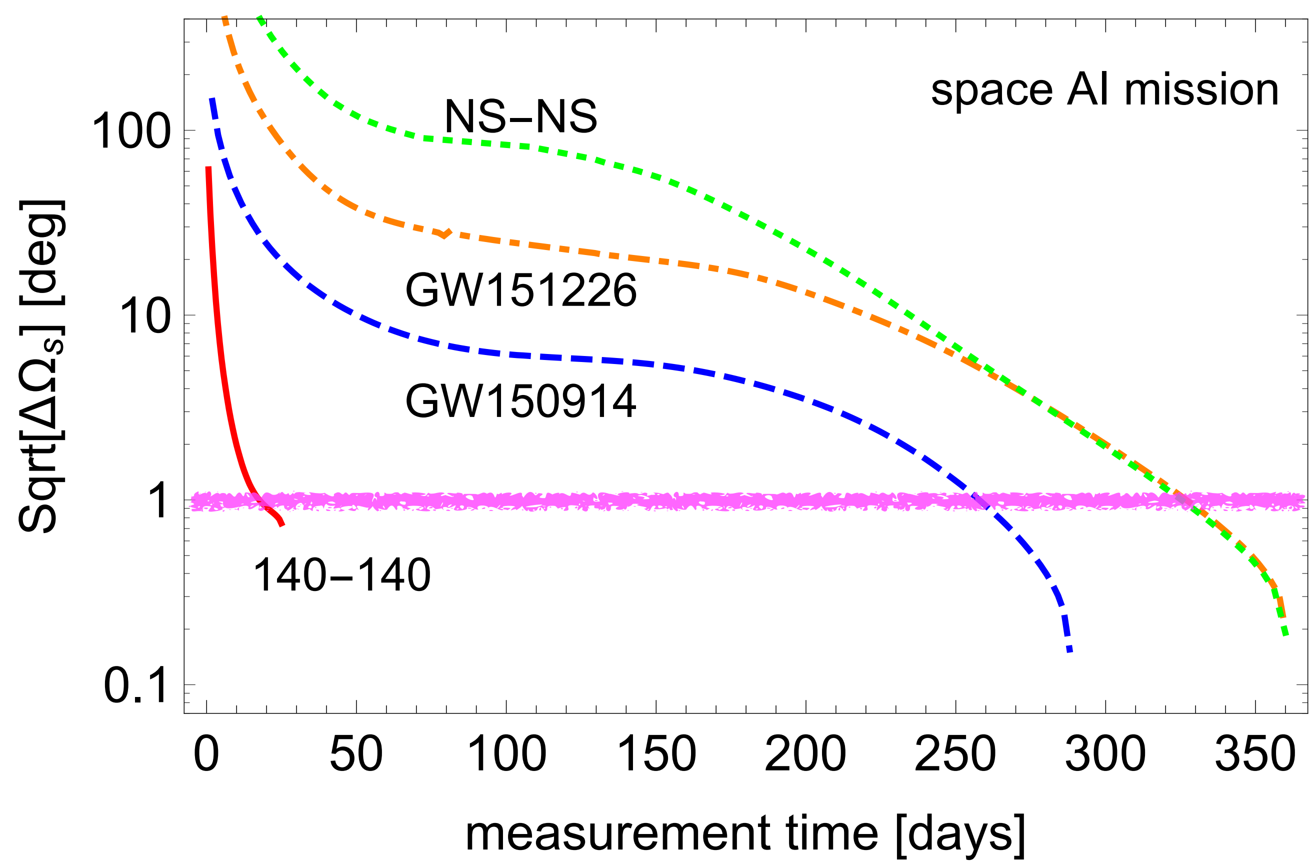
Angular Localization

Benchmark	distance D_L	lifetime	Satellite Detector $\sqrt{\Omega_s}$ [deg]	SNR
GW150914	410 Mpc	9.6 months	0.16	67
NS-NS	140 Mpc	140 years	0.19	5.2
140-140	410 Mpc	25 days	0.75	190



localize within FOV of many EM telescopes,
predict mergers > 1 week advance warning
improves multi-messenger astronomy

changes observing strategy
earth orbit optimal



2 optimal terrestrial detectors could localize observed NS-NS to ~ 1°, predict ~ 1 day ahead

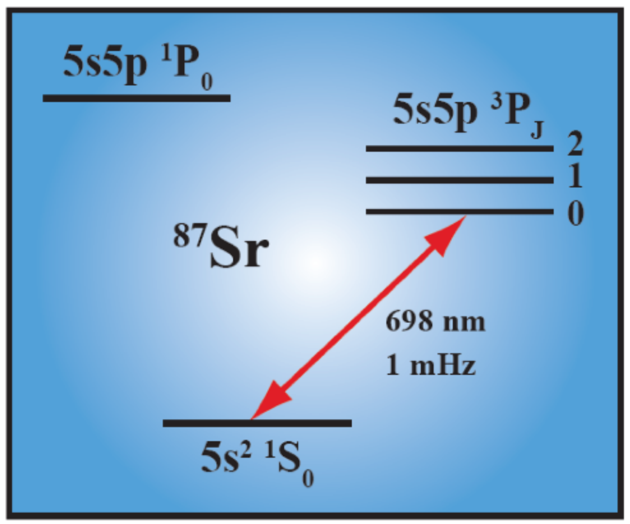
PWG + Sunghoon Jung PRD **97** (2018)

Dark Matter Detection with MAGIS

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

MAGIS could also detect ultralight dark matter (e.g. axions)

such DM acts like a field, can oscillate fundamental ‘constants’ e.g. electron mass

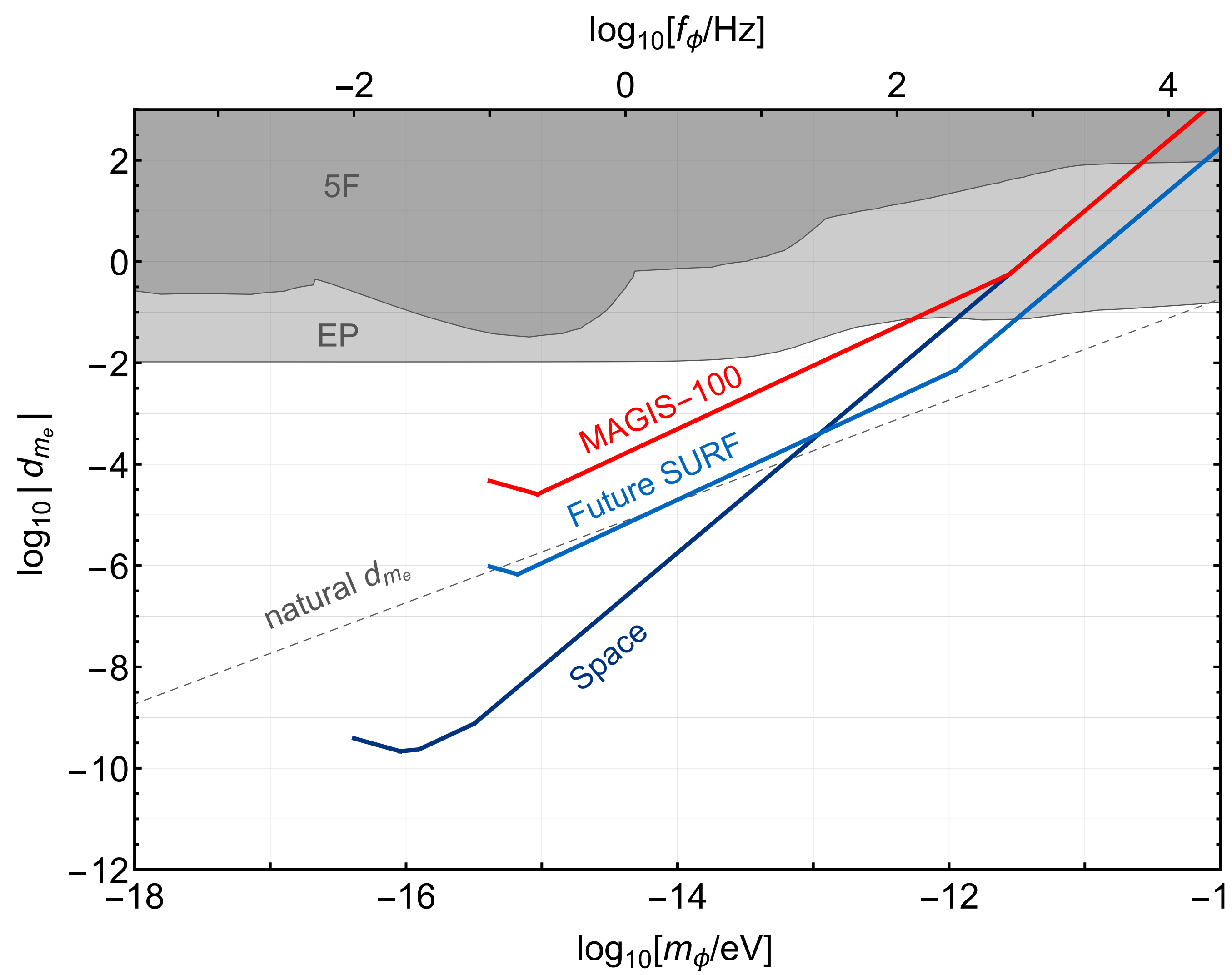


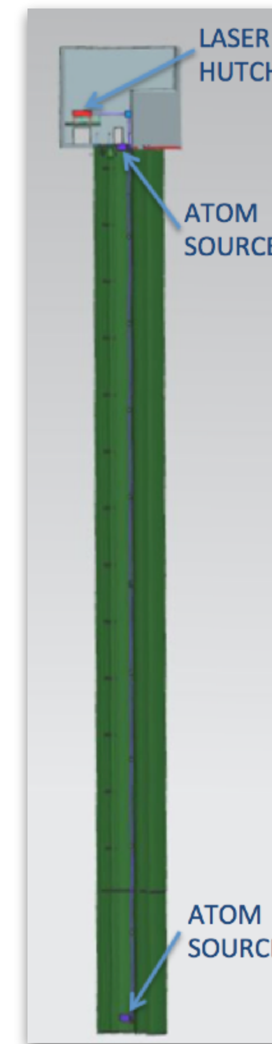
Clock transition in candidate atom ⁸⁷Sr

energy splitting will oscillate with fixed frequency

only observable if compare two clocks ➜ GW detector

not observable in laser interferometer GW detector



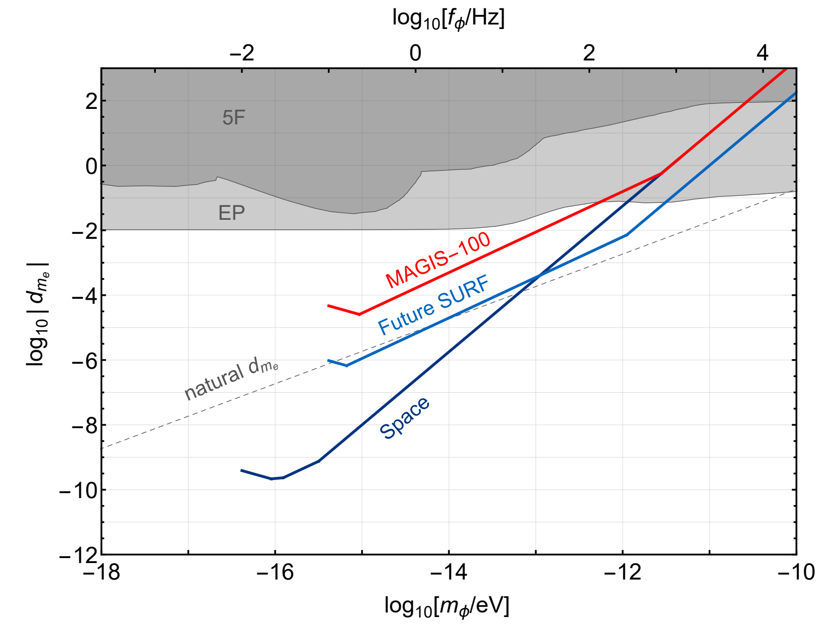


Dark Matter Detection with MAGIS

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

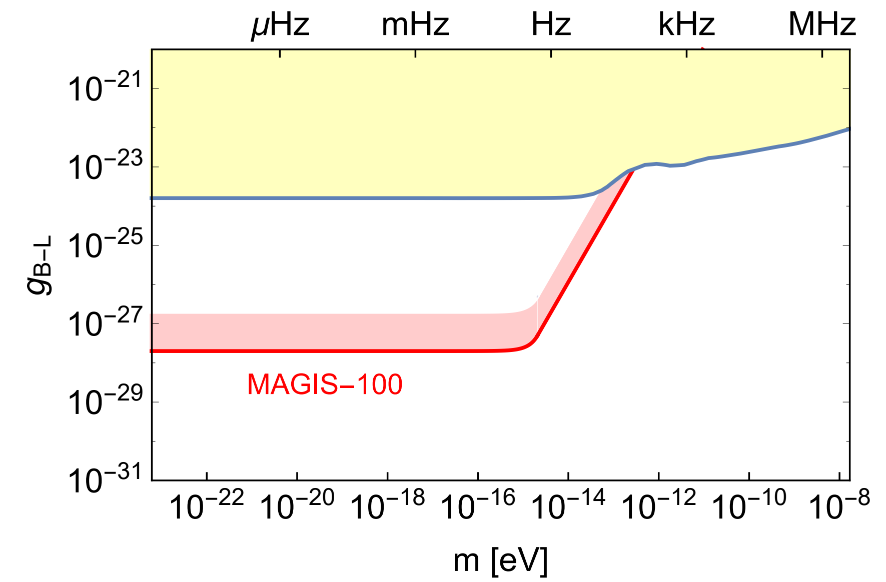
1. single-baseline "gravitational wave" search

   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)