Cosmology from the outer Solar System

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actual photo from SpaceX of Tesla that orbits out to Mars

What does the few-decades future of cosmology look like?

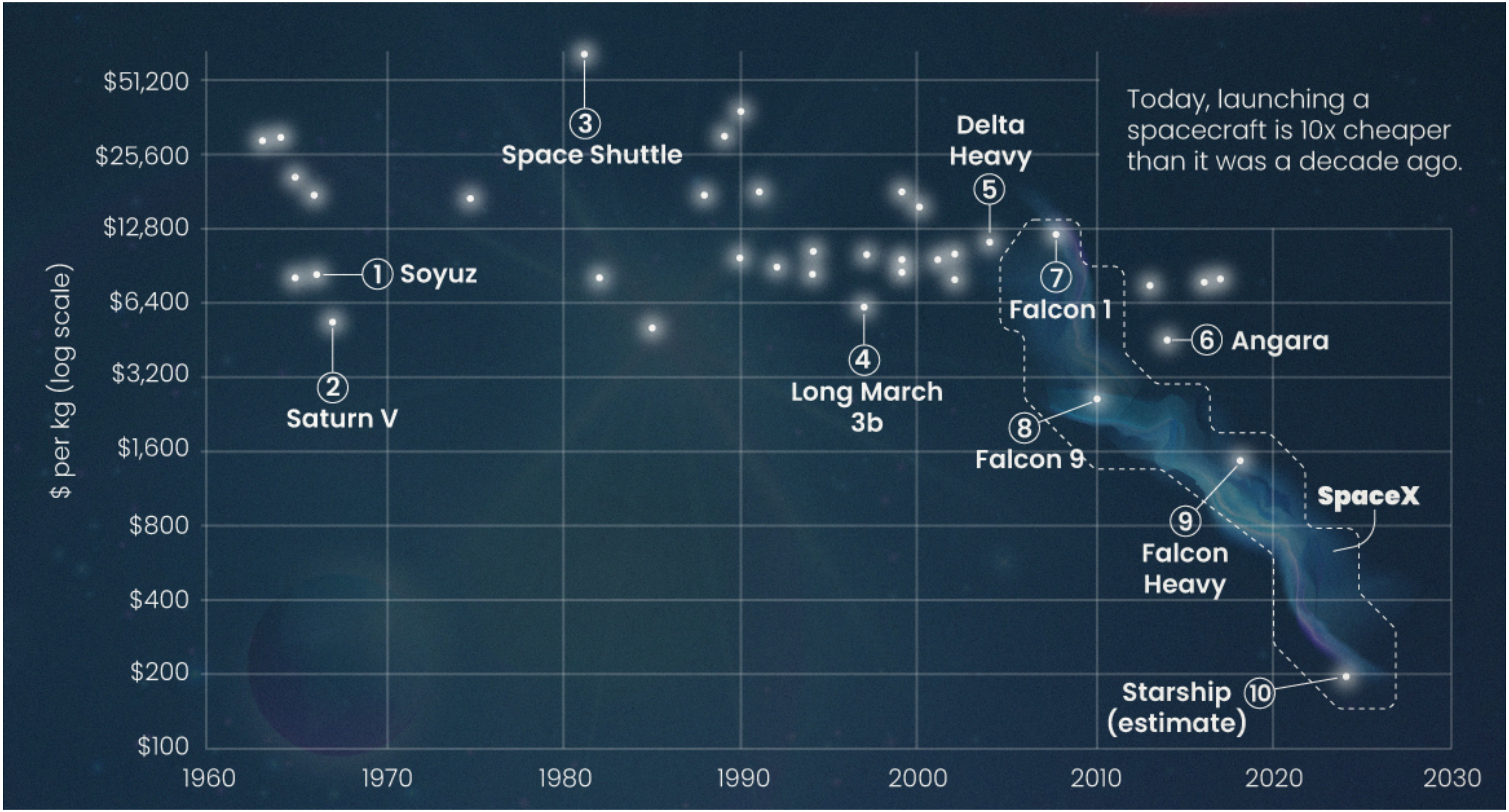
We will have mapped the CMB to cosmic variance, cosmic structure over the redshifts where we can do optical galaxy surveys, intensity mapping I'm not sure, LISA will have probed $10^{-4} - 1$ Hz gravity waves of intermediate mass nuclear black holes, ...

This talk: Potentially groundbreaking cosmology that can be done with radio dishes in the outskirts of our Solar system

- geometric measurements of expansion of universe to nail down late-time expansion history *(Briefly at end)*
  Boone & McQuinn arXiv:2210.07159 — million-x angular res. of Gaia
- kpc-AU clumpiness of the dark matter *(Extremely briefly)*
  Xiao, Dai, & McQuinn arXiv:2401.08862
- μHertz frontier for gravitational waves *(Deep dive)*
  ~1 month from being posted

All ideas involve sending (maybe the same) spacecraft to the outer Solar System.
The technology on each spacecraft is similar to a GPS satellite.

One motivation: the cost of launch is plummeting

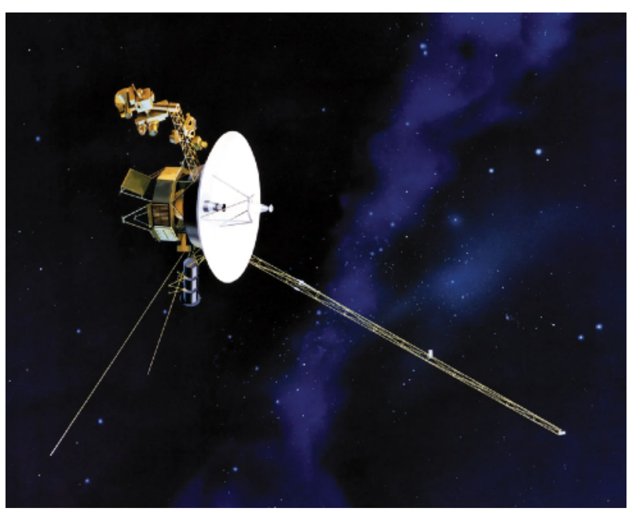


It's nearing the $10/kg for me to visit Berkeley!.

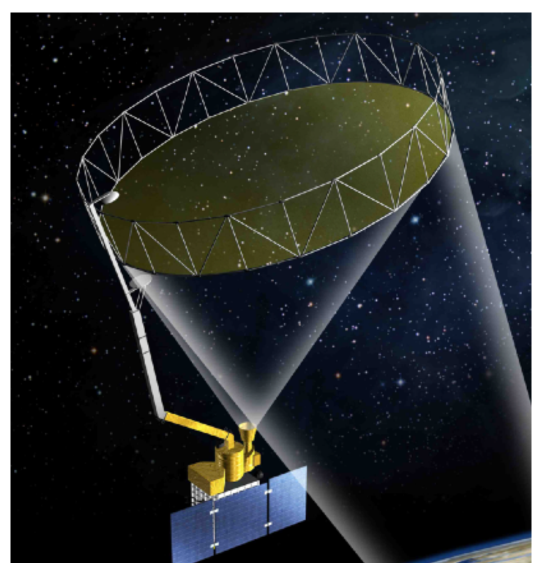
The cost is all in developing the spacecraft, whether it goes into low earth orbit or to the outer Solar System

But putting spacecraft in outer Solar System is hard!!!!

- it takes a long time to get out there *(took 500 kg New Horizons ten years to get to Pluto at 34 AU)* Could get out there twice as fast with newest rockets.
- rely on radioisotope power sources, where the power for entire spacecraft might be just 250 Watt *(science system can only take a fraction)*
- downlinks are ~10-100 kbps
- we also will want a radio dish too — fortunately, there are lightweight radio dishes



Voyagers at 100AU & Cassini had 4 meter dishes



SMAP — a 6 meter, 56 kg compressible mesh dish

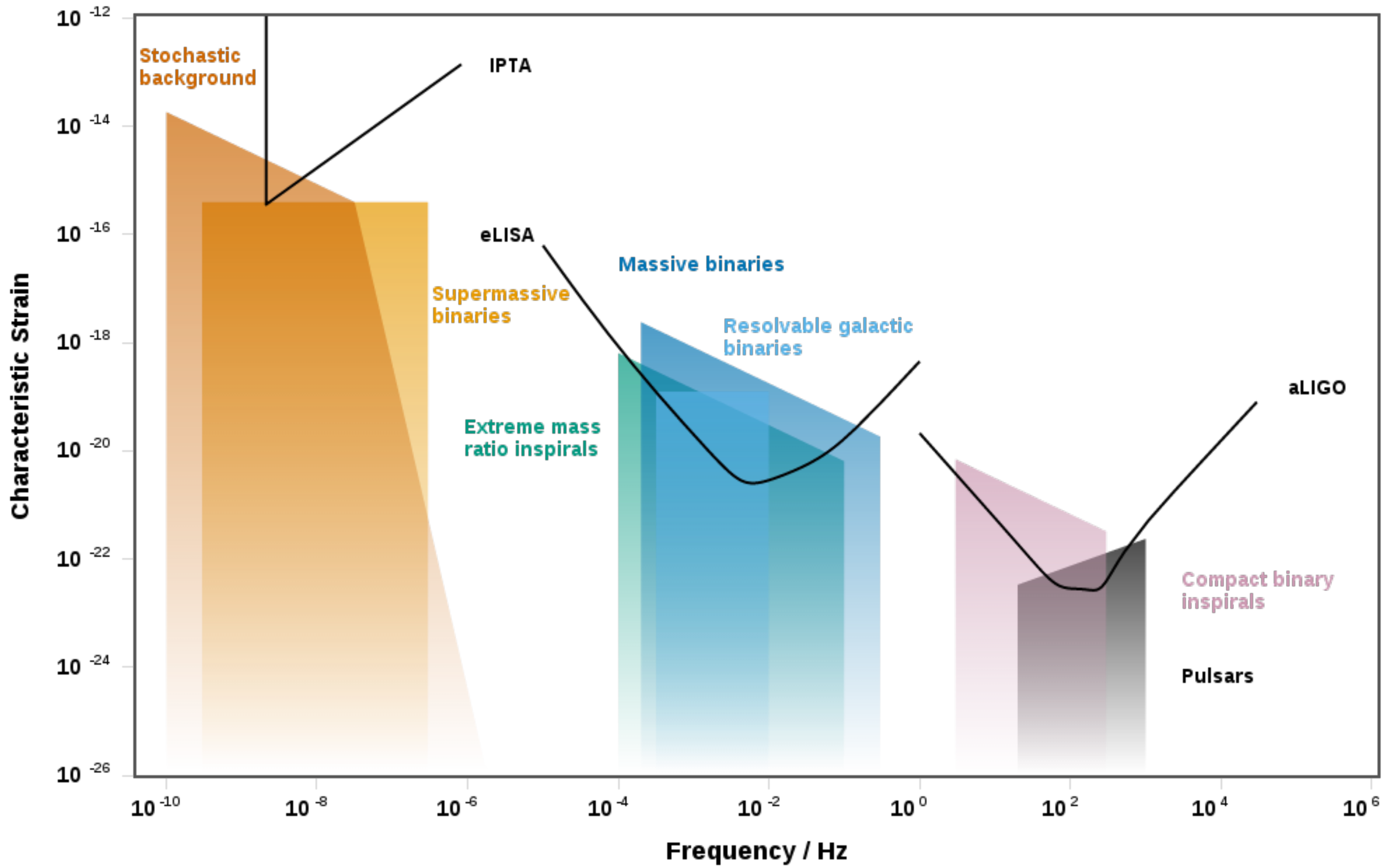
RadioAstron — a 10 meter fold out dish that orbited out to the Moon

There are telecommunication satellites with 20 meter mesh dishes!

Could radio dishes in outer Solar System be interesting for gravitational waves?

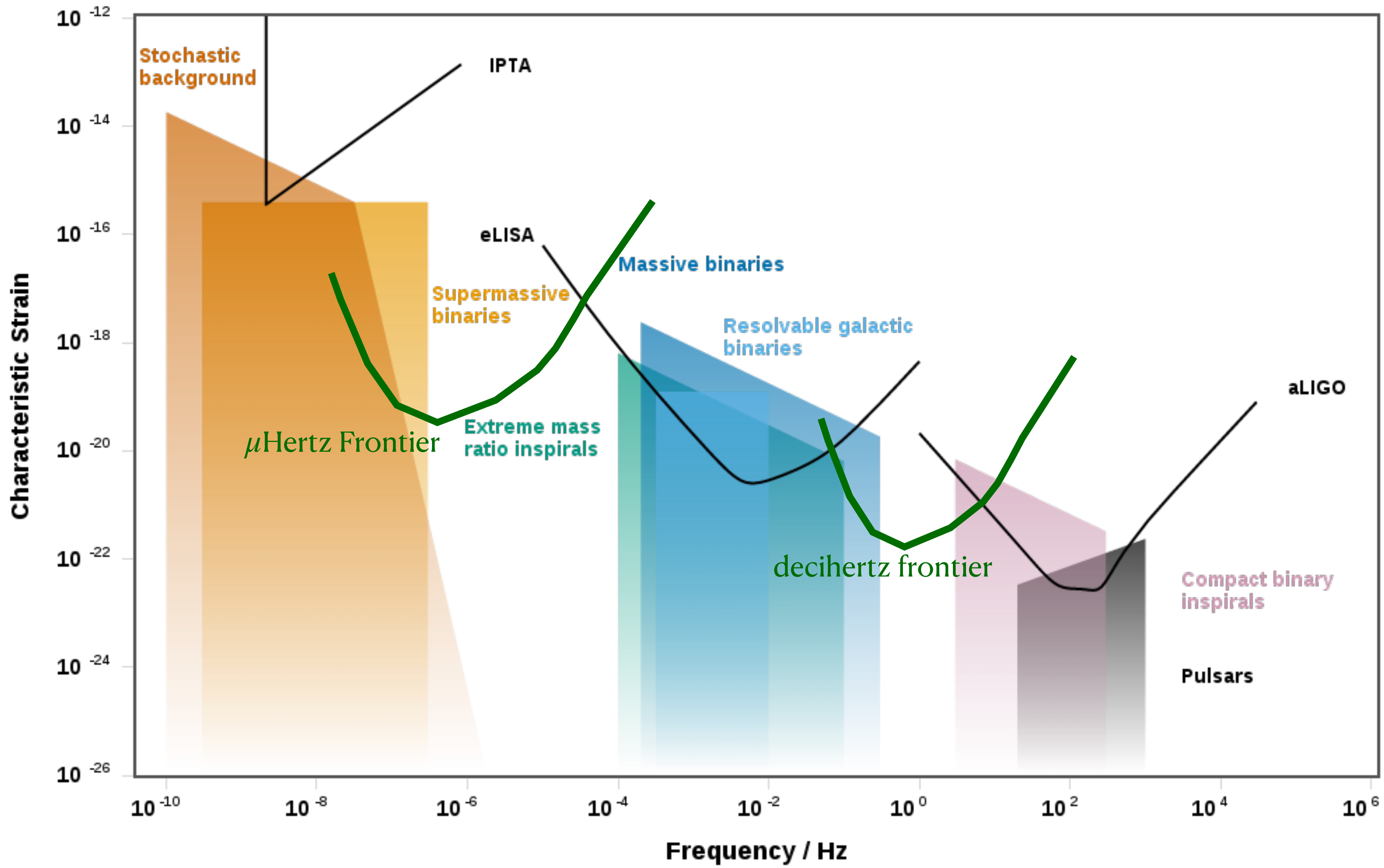
The gravitational wave landscape

Image Credit: Christopher Berry



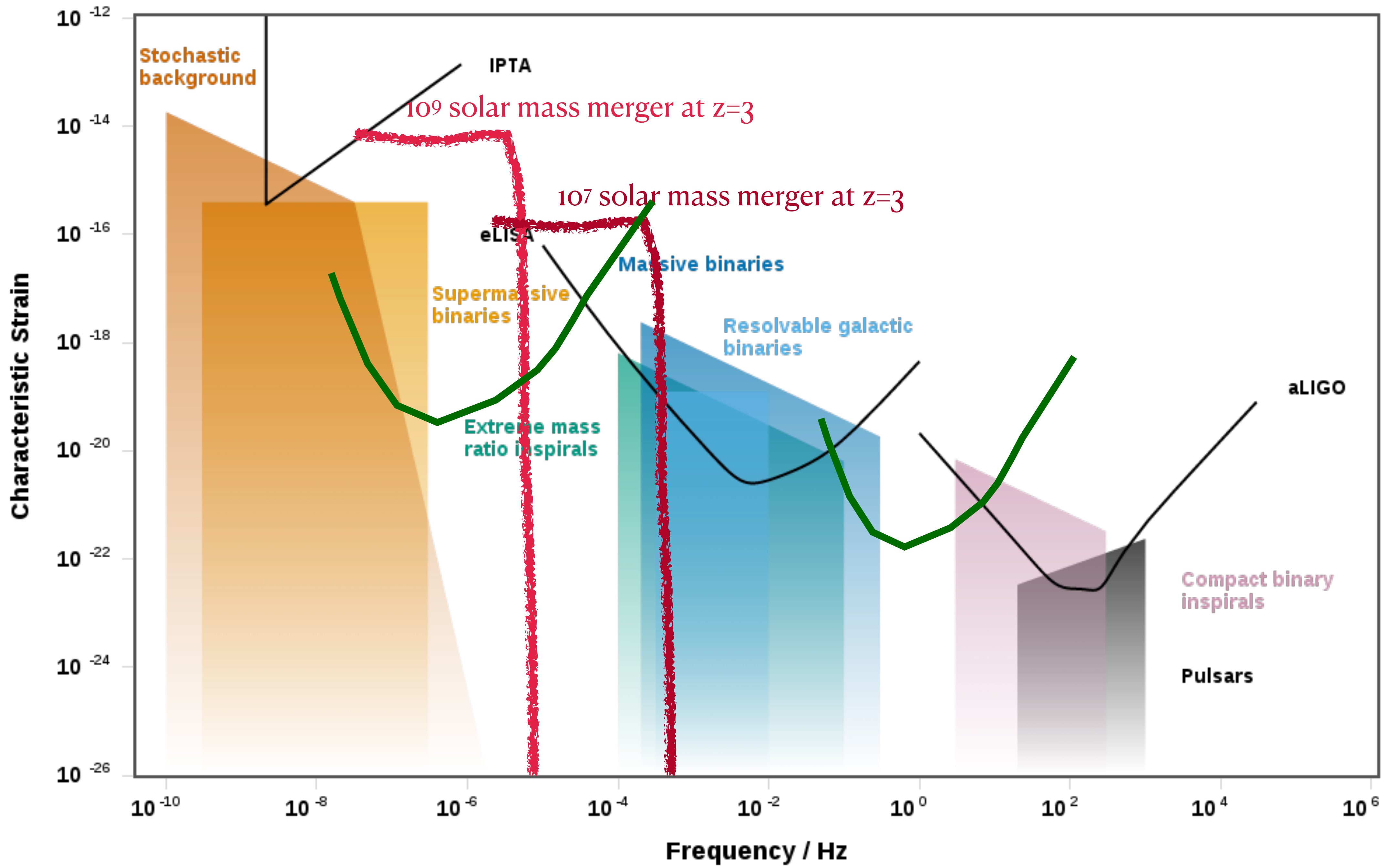
The gravitational wave landscape

Image Credit: Christopher Berry



Quick tutorial on characteristic strain

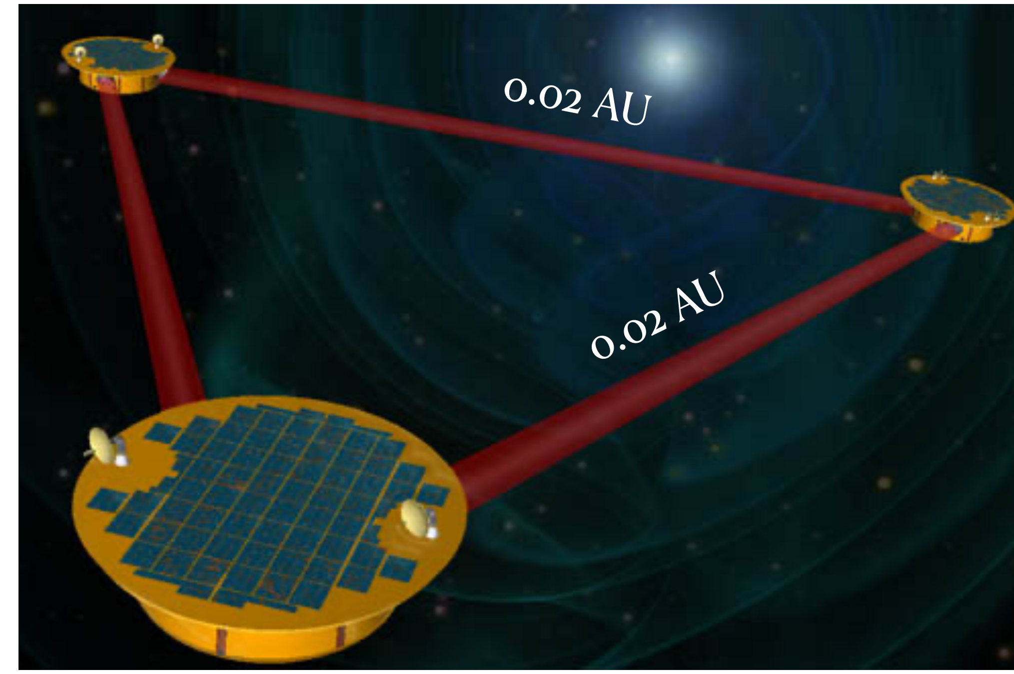
Image Credit: Christopher Berry



$$\left(\frac{S}{N}\right)^2 = \int d\log\nu \left(\frac{\text{characteristic strain}}{\text{sensitivity curve}}\right)^2$$

How will LISA work?

I'm in awe of LISA



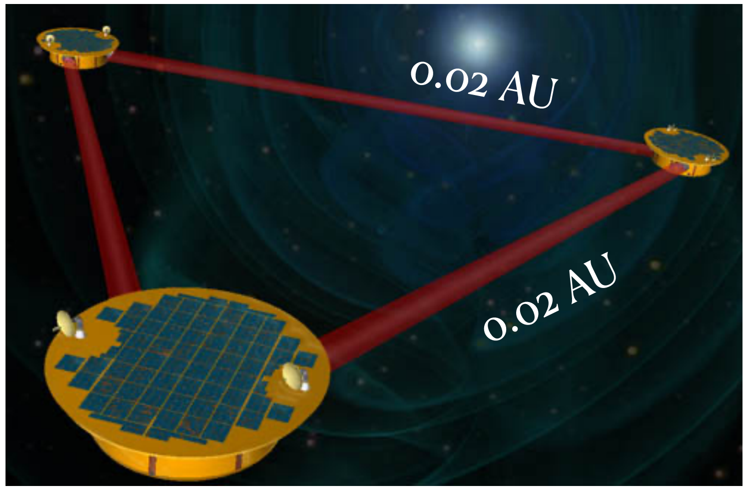
- sends 2 Watt lasers between each satellite separated by 0.02AU that are phased up to each other so electric field along arm is $E = E_0 \exp[i\phi(t_{\rm em})]$ where $\phi(t_{\rm em}) \approx \omega\, t_{\rm em}$ and ω the γ's frequency
- measure phase difference of incoming beam with home satellite

$$\text{arm } 1: \quad \Delta\phi_1 = \phi(t-2L) - \phi(t) + \omega L\, h_1$$
$$\text{arm } 2: \quad \Delta\phi_2 = \phi(t-2L) - \phi(t) + \omega L\, h_2$$

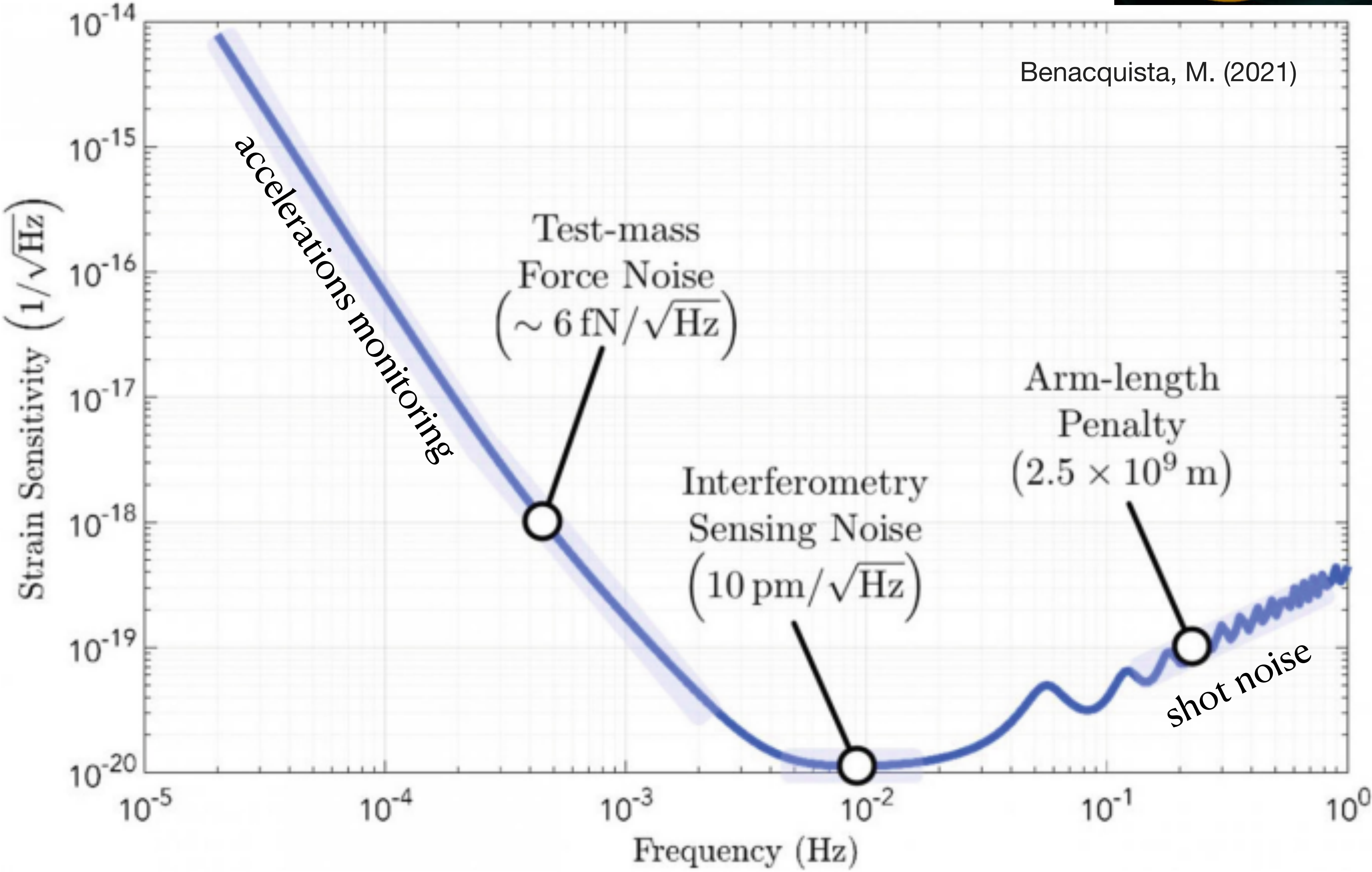
where h_X is the gravity wave along arm X (assuming $\omega L \ll 1$).

- Observable "is" $\Delta\phi_1 - \Delta\phi_2$ as this cancels clock noise in $\phi(t)$

LISA's sensitivity

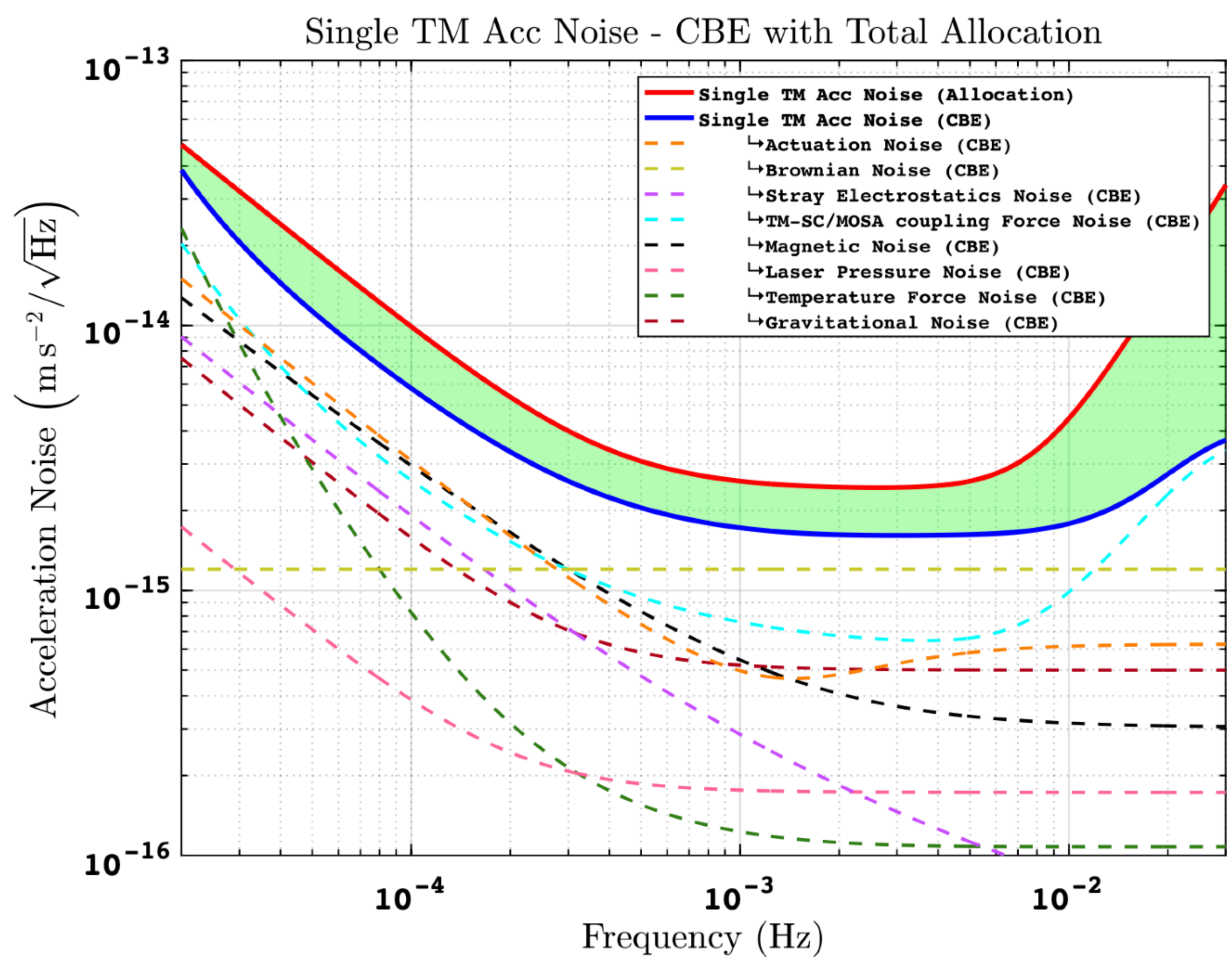


$$\delta\Delta\phi = \omega\delta x + \delta\phi_{\text{shot}}$$



To detect μHz gravitational waves with LISA- like array, we need significant improvement in acceleration technology on long timescales.

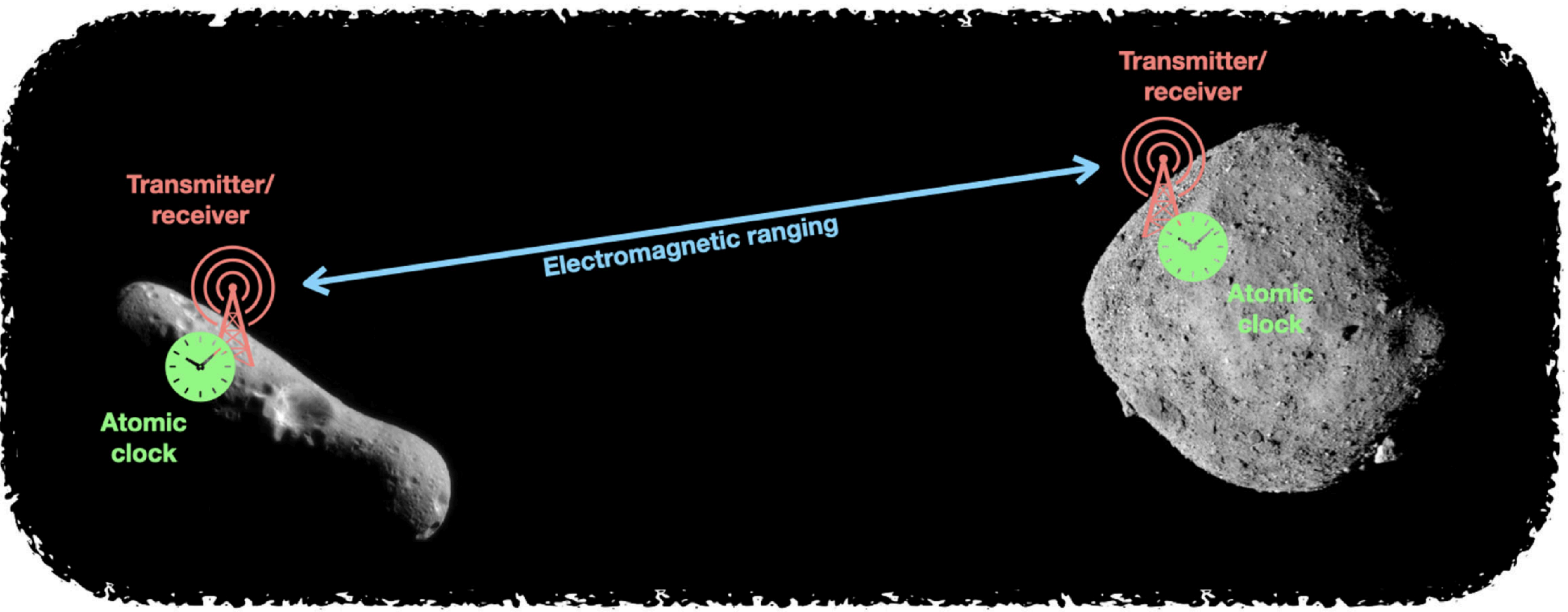
A lot of the sophistication of LISA is already in measuring accelerations.



Frequencies we are interested in!

An idea to avoid measuring accelerations: establish bases on near-earth asteroids

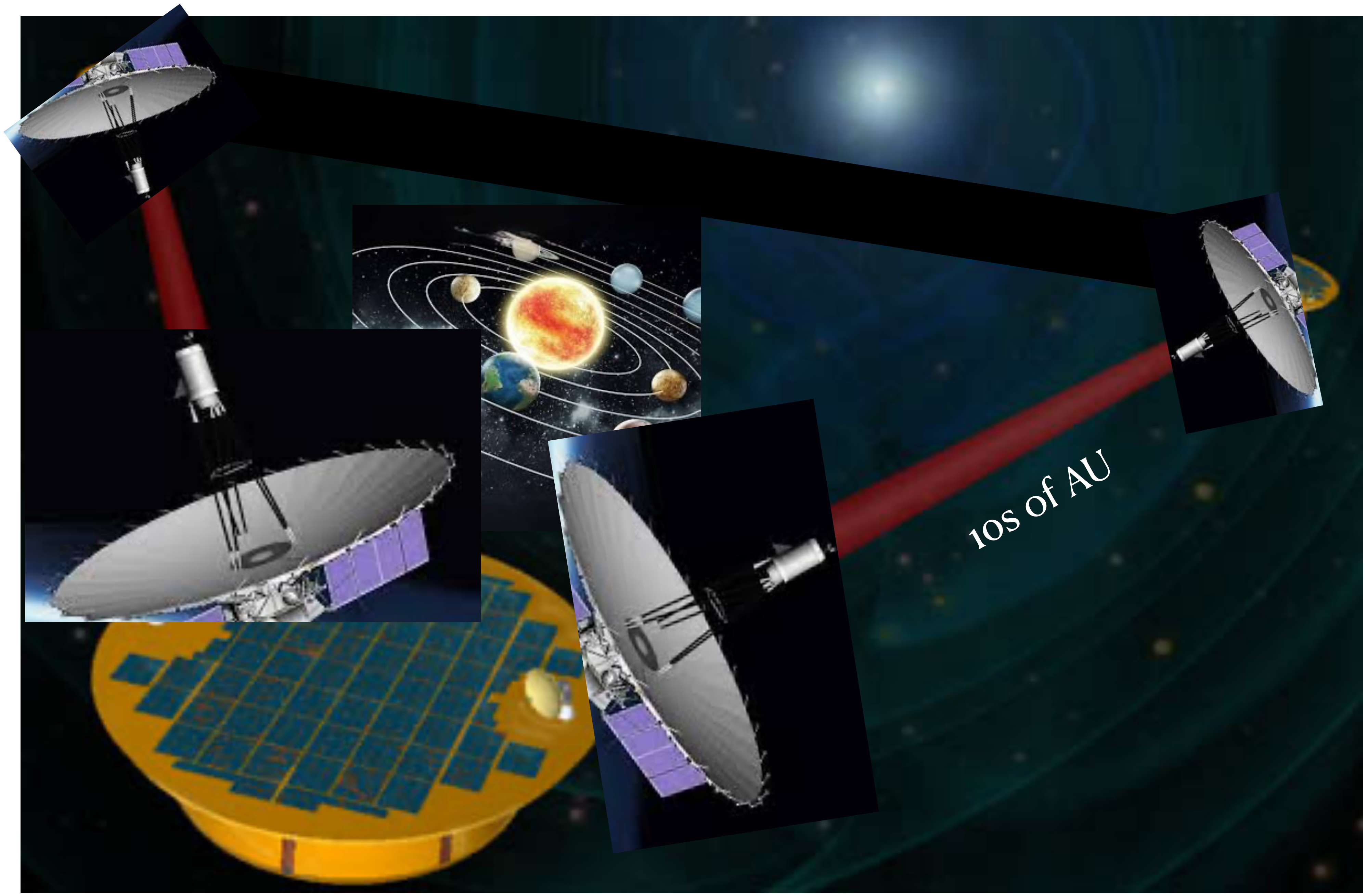
these are great test masses (and hopefully not too seismic)



Idea requires thousands of times better clocks than we have sent to space.

Fedderke et al 2022

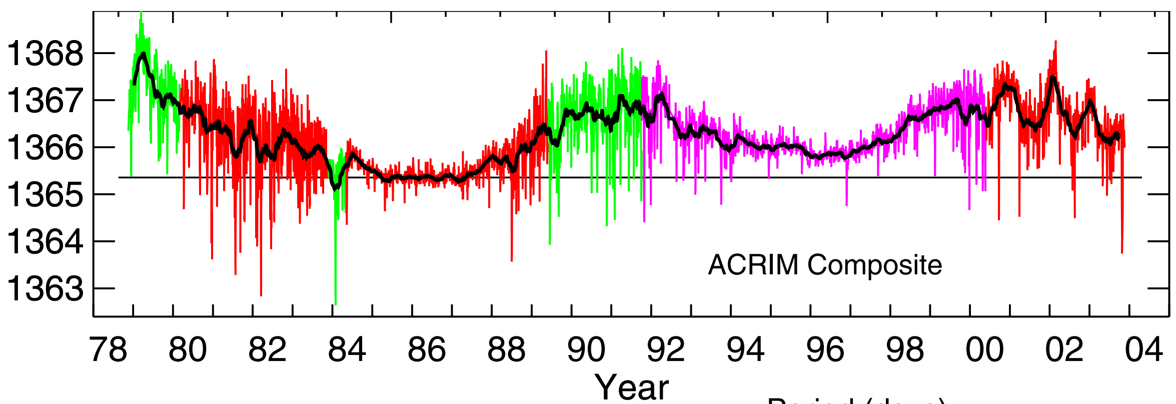
This talk considers whether the outer Solar System could be another way to avoid needing acceleration control.

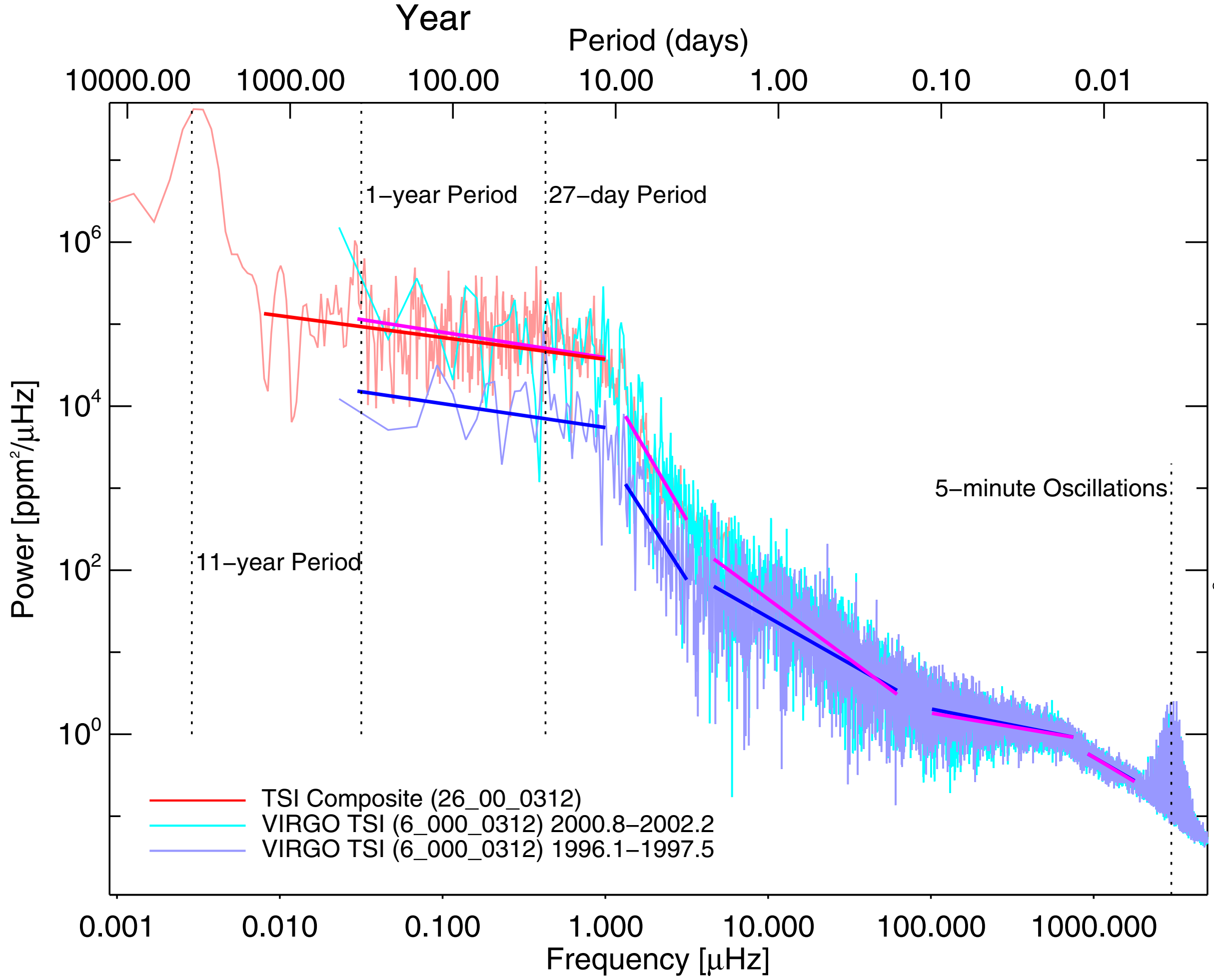


Maybe this is done with lasers or maybe with radio broadcasts

Key idea: The dominant accelerations go way down if you go to outer Solar System

Solar irradiance variations ($\propto 1/r^2$)

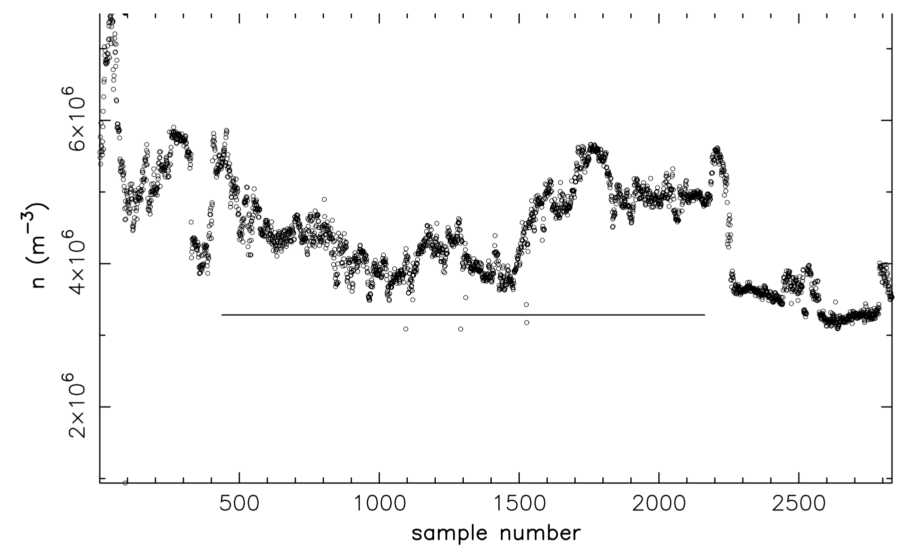


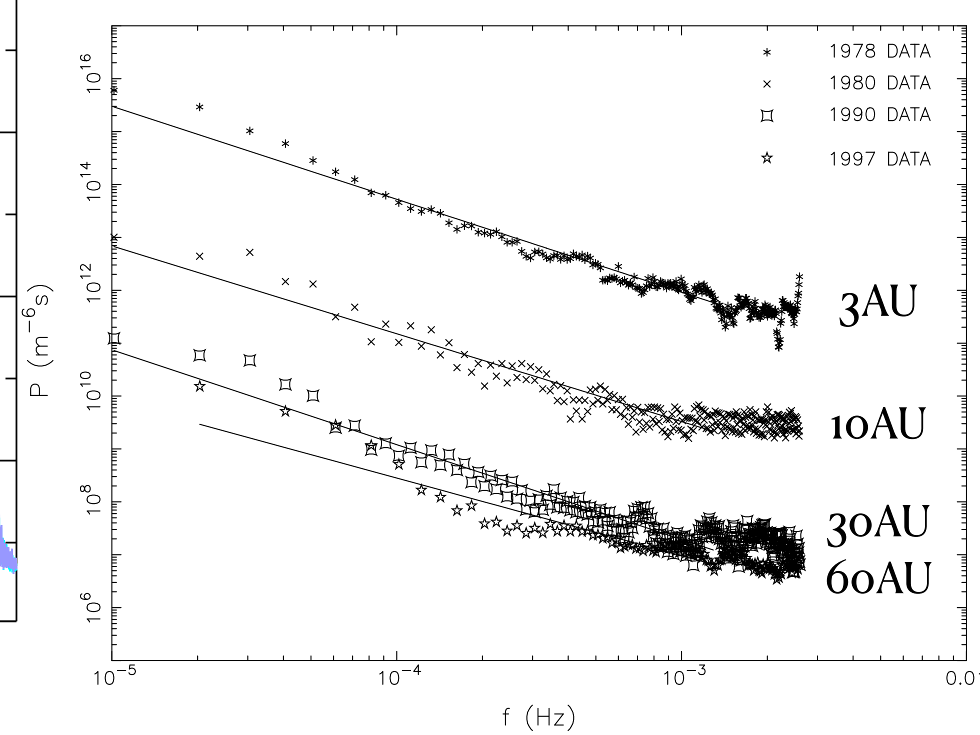


Frohlich & Lean 2004

Solar wind drag ($\propto 1/r^{2\text{ish}}$)

Density variation a la Voyager 2



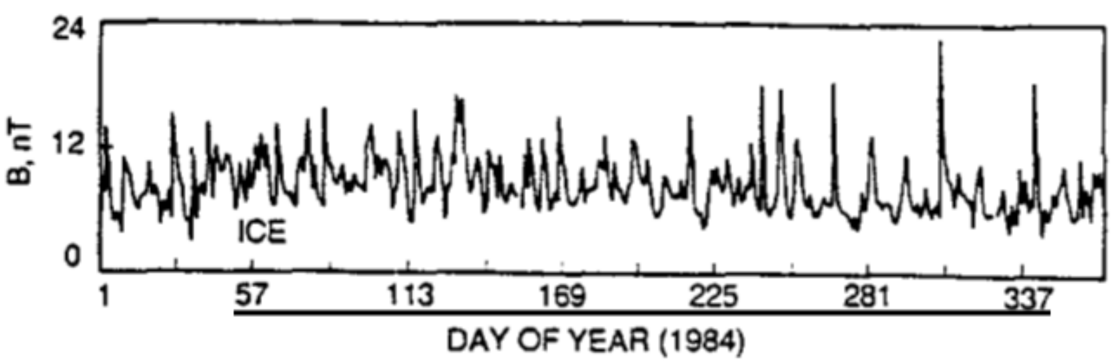


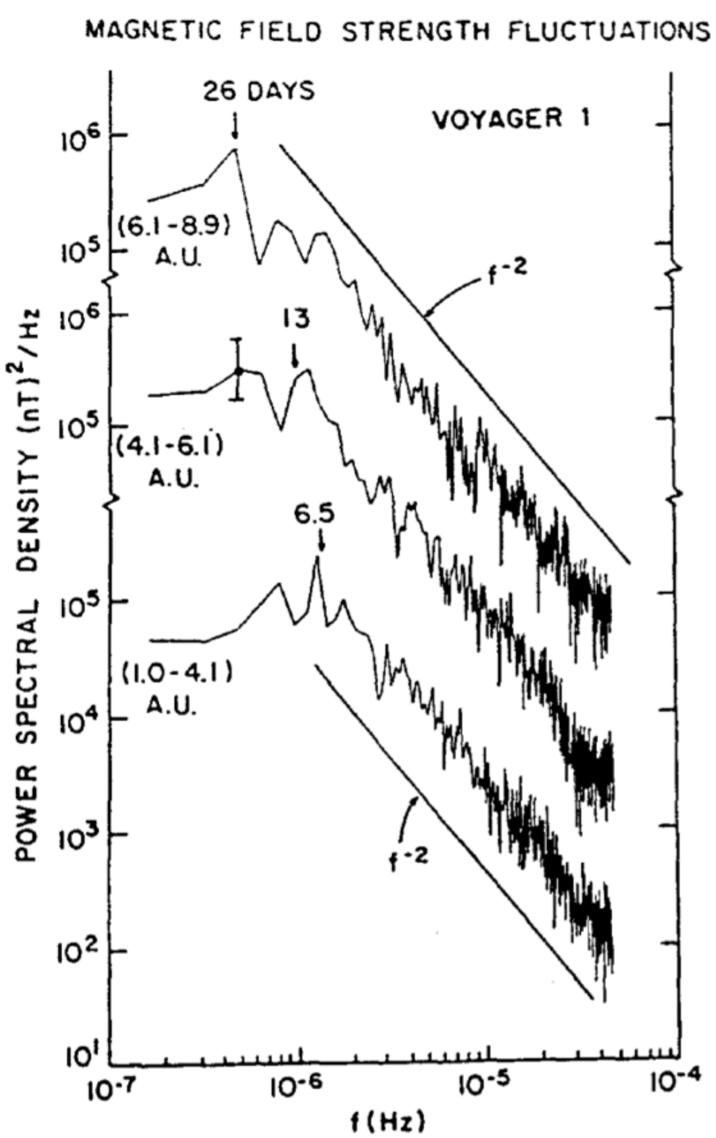
Bellamy, Cairns, & Smith 2005

Some accelerations are more constant in radius

Lorentz force from magnetic fields

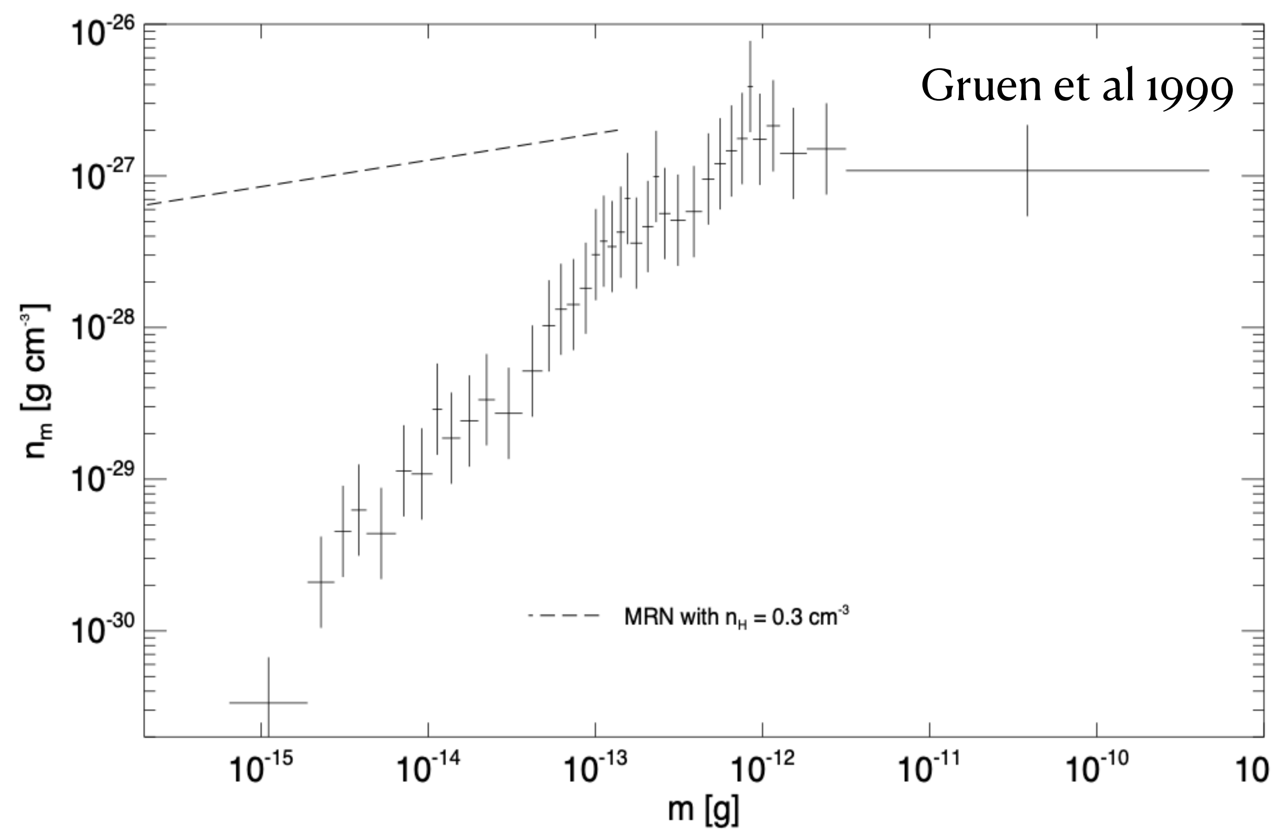
Magnetic field from Voyager 2 at 16 AU





collisions from dust particles

spectrum of interplanetary dust



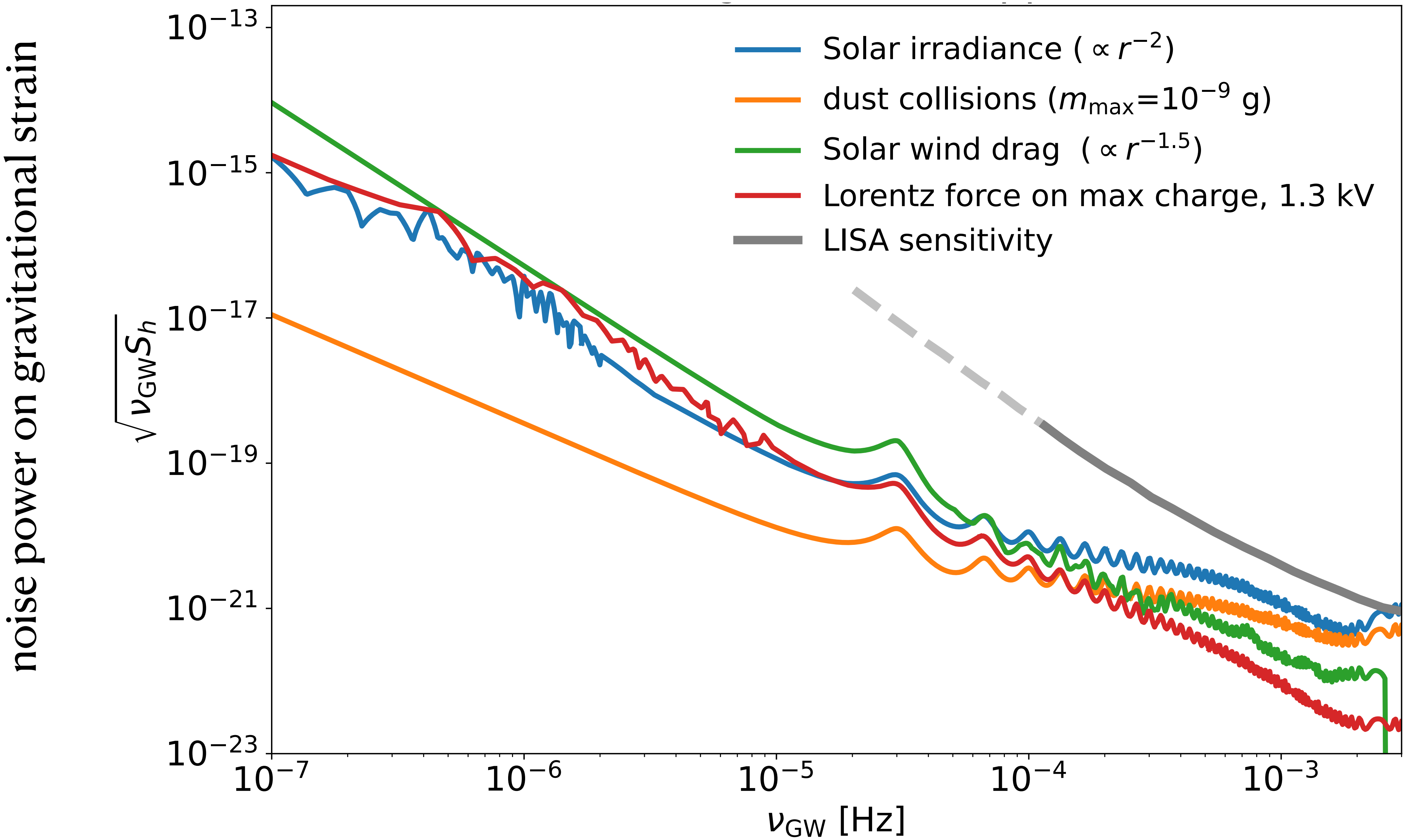
Each collision results in a delta-function acceleration
— calculating the acceleration power spectrum is like calculating the 1 halo term in halo model :)

Gravitational accelerations are negligible for our experiment.

How accelerations translate into gravitational wave sensitivity

$(\delta\Delta\phi = \omega\delta x = \omega\delta a/(2\pi\nu_{\mathrm{GW}})^2$ since $\delta a \equiv \ddot{\delta x})$

Assumes a 1000 kg spacecraft with area 10 m² at 30AU



These are sensitivity curves assuming infinite power in lasers or radio broadcasts....that's next

Shot or thermal noise

Shouldn't this noise be too large? — our detectors are 1000x more separated than LISA's! No actually it seems okay.

$[C/N_0]_{\mathrm{dB-Hz}} \approx 35$ is the *acquisition threshold* above which your cell phone can lock onto GPS signal from satellites. The Deep Space Network can acquire lock onto the ranging signal from satellites at $[C/N_0]_{\mathrm{dB-Hz}} = 15$. The carrier wave is always modulated by lower frequency pseudorandom code so that these weak signals do not correlate with other things.

- lasers

$$
\begin{aligned}
[C/N_0]_{\mathrm{dB-Hz}} &= 10\log_{10}\frac{P_{\mathrm{rec}}}{2\eta hc/\lambda} \\
&= 33\,\mathrm{dB\text{-}Hz} + 10\log_{10}\left(\frac{P_{\mathrm{em}}}{10\ \mathrm{W}}\right) + 20\log_{10}\left(\frac{D}{20\ \mathrm{cm}}\right) \\
&\quad -20\log_{10}\left(\frac{L}{30\ \mathrm{AU}}\right) - 10\log_{10}\left(\frac{\lambda}{1\mu\mathrm{m}}\right),
\end{aligned}
$$

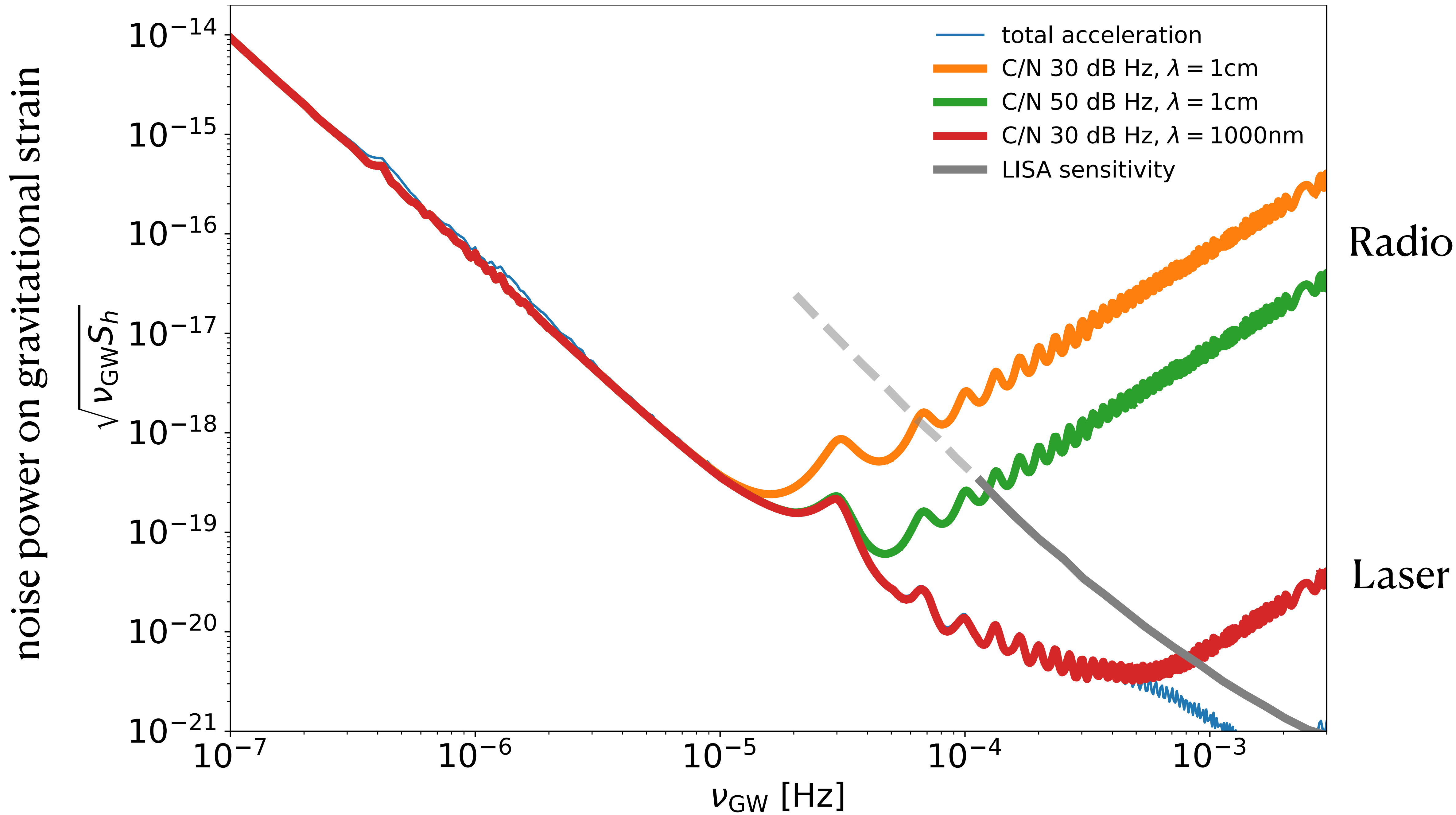
- radio

$$
\begin{aligned}
[C/N_0]_{\mathrm{dB-Hz}} &= 10\log_{10}\left(\frac{P_{\mathrm{rec}}}{kT_{\mathrm{sys}}}\right), \\
&= 34\,\mathrm{dB\text{-}Hz} + 10\log_{10}\left(\frac{P_{\mathrm{em}}}{10\ \mathrm{W}}\right) + 20\log_{10}\left(\frac{D_{\mathrm{eff}}}{5\ \mathrm{m}}\right) - 10\log_{10}\left(\frac{T_{\mathrm{sys}}}{50\ \mathrm{K}}\right) \\
&\quad -20\log_{10}\left(\frac{L}{30\ \mathrm{AU}}\right) - 20\log_{10}\left(\frac{\lambda}{1\ \mathrm{cm}}\right),
\end{aligned}
$$

Once locked, then this is the phase error is $\widetilde{\phi}_{\mathrm{rms}} = 0.01 \times 10^{-\left([C/N_0]_{\mathrm{dB-Hz}} - 40\right)/20}$ rad $\mathrm{Hz}^{-1/2}$

Total sensitivity including realistic shot/thermal noise

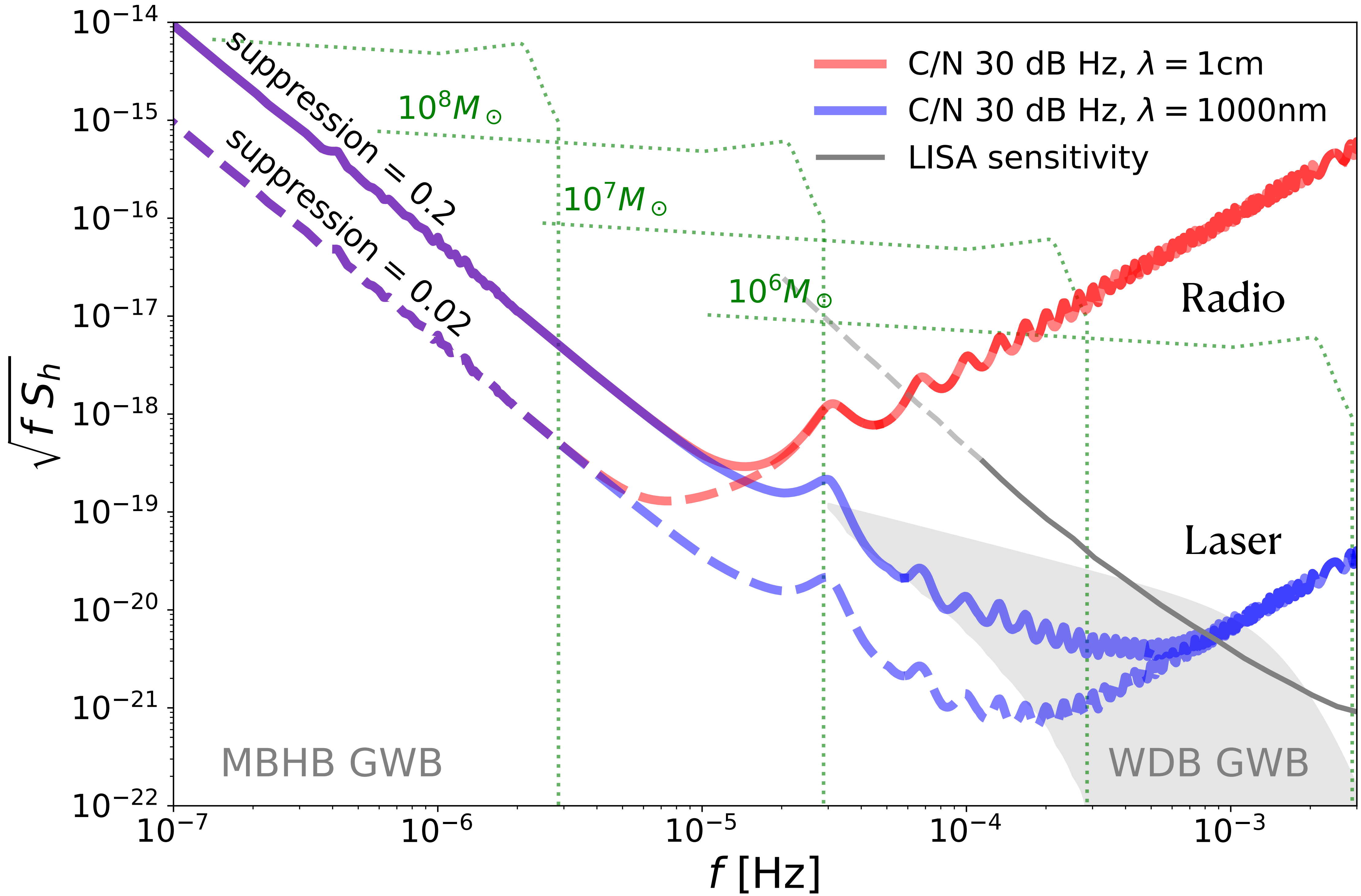
Assumes a 1000 kg spacecraft with area 10 m² at 30 AU and 30AU arms



Lasers are more sensitive, but come with extra challenges that we will get to

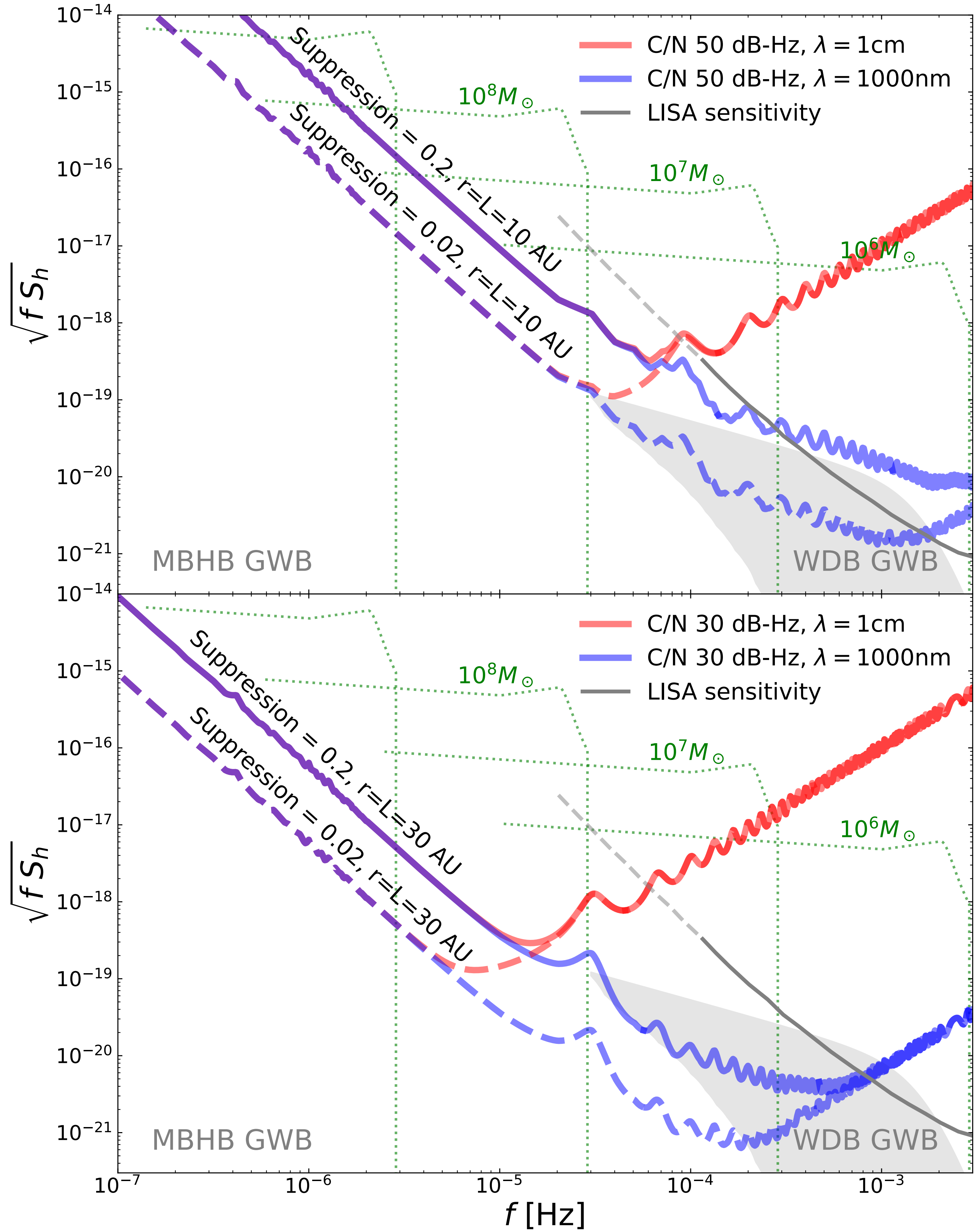
Total sensitivity of concept

Assumes a 1000 kg spacecraft with area 10 m² at 30 AU and 30AU arms



Note that once detector becomes sensitive to the stochastic background (grey), there is little point in making it more sensitive.

10 AU vs. 30AU



C/N 50 dB-Hz, $\lambda = 1$cm
C/N 50 dB-Hz, $\lambda = 1000$nm
LISA sensitivity
Suppression = 0.2, r=L=10 AU
Suppression = 0.02, r=L=10 AU
$10^8 M_\odot$
$10^7 M_\odot$
$10^6 M_\odot$
MBHB GWB
WDB GWB
C/N 30 dB-Hz, $\lambda = 1$cm
C/N 30 dB-Hz, $\lambda = 1000$nm
LISA sensitivity
Suppression = 0.2, r=L=30 AU
Suppression = 0.02, r=L=30 AU
MBHB GWB
WDB GWB
$\sqrt{f\,S_h}$
f [Hz]

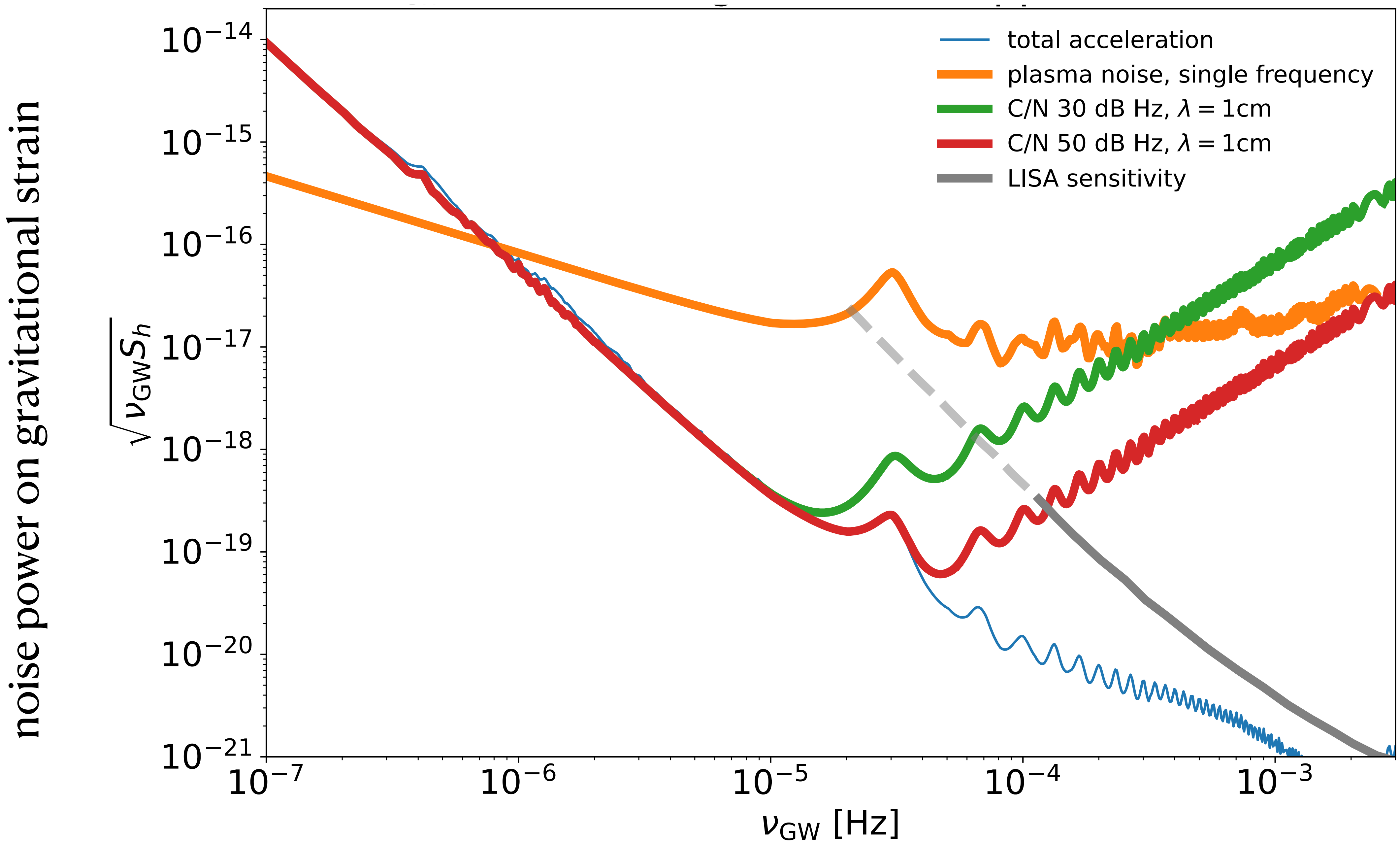
Why radio dishes may be much easier than lasers

- For lasers, detector spacecraft relative velocities are a huge issue because $\Delta\phi_1 - \Delta\phi_2 \approx \omega \; v/c \; t = 2\pi f_{\rm het} t$.   "Clock" errors now enter proportional to $f_{\rm het}$!
  - LISA must keep $f_{\rm het} < 20$MHz, which it does by limiting relative velocities to 10 m/s of spacecraft and a schedule of adjusting relative laser frequencies
  - outer solar system spacecraft likely need at least order of magnitude larger $f_{\rm het}$ and hence a much better clock
- Intensity variations in lasers at frequency of gravitational waves also needs to be precisely controlled, but this is not an issue in radio

since sensitivity gains for laser concept are mostly probed by LISA, maybe radio is the way to go

For radio, there is plasma dispersion noise as plasma adds some extra phase.

Assumes a 1000 kg spacecraft with area 10 m² at 30 AU and 30AU arms



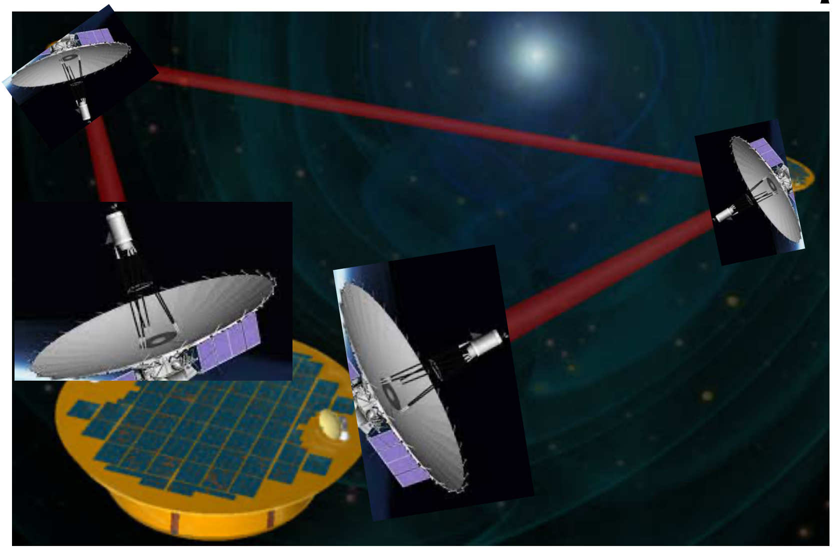
Need two frequencies to get rid of plasma noise at cost of factor of ~1.5 in sensitivity.

The next order plasma effect from refraction is very small.

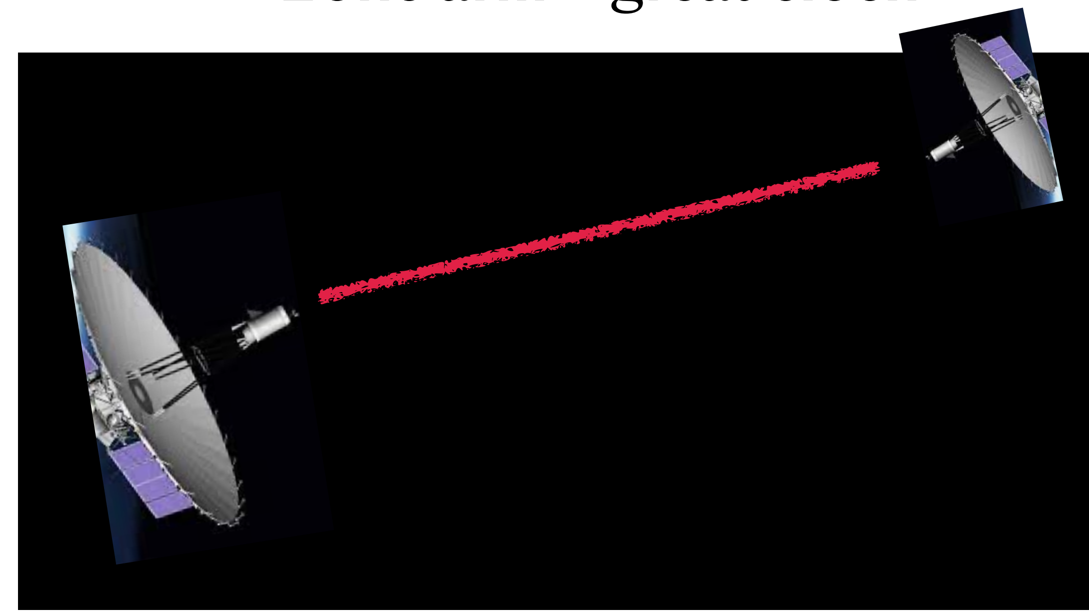
Clock noise

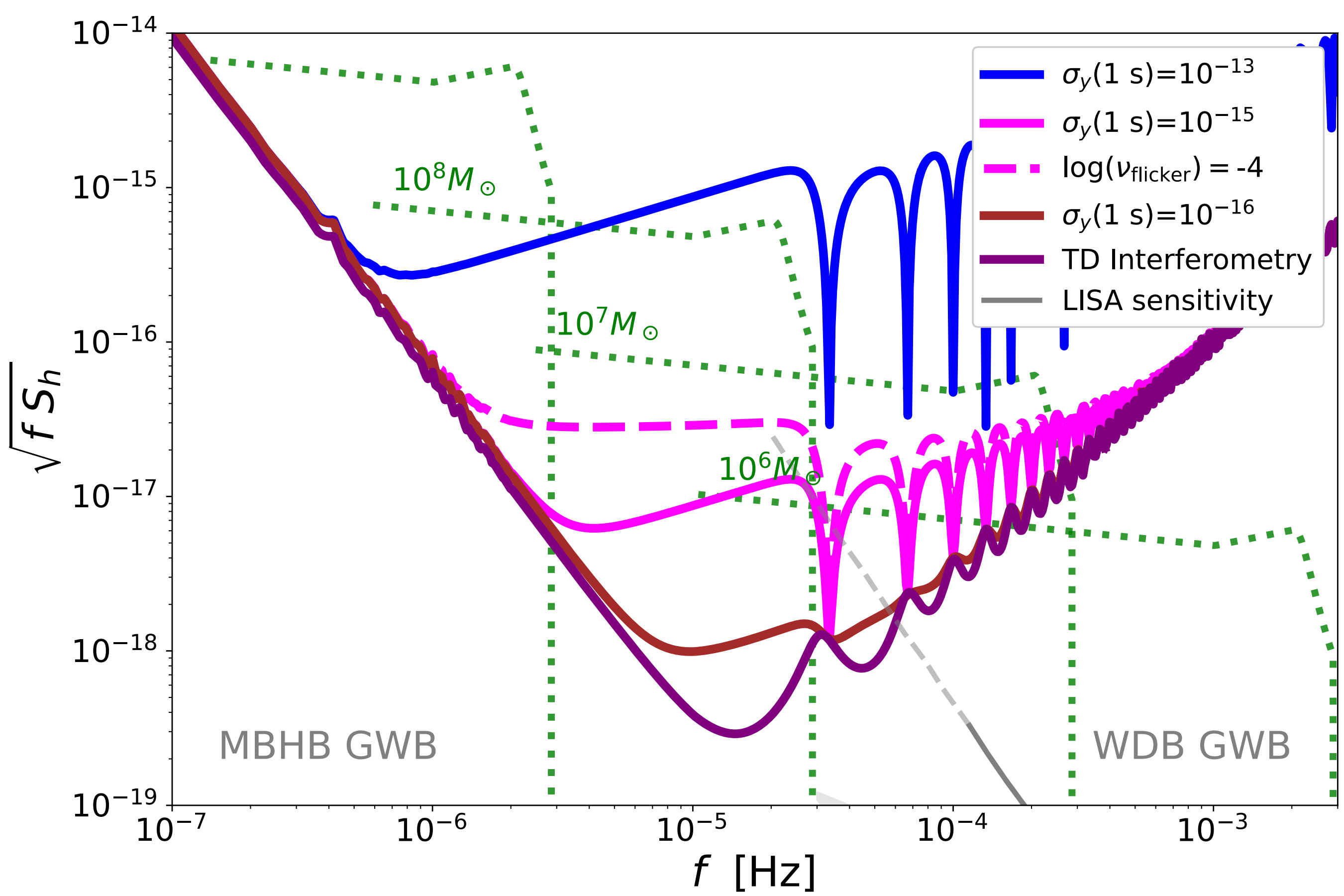
either you need to do `Michelson' interferometry or very precise atomic clocks

Two dishes on one 'mothership'



Lone arm + great clock





10^{-13} = Allan variance of best atomic clocks in space
Best atomic clocks on earth are 10^{-19}

Clock noise doesn't dominate error (for radio case) once clock is 1000 times more precise than best atomic clock in space. So unfortunately need one satellite with two dishes/lasers like LISA without significant developments in space-clock technology.

What about getting data back?

Remember, we can rely on only 10-100 kbps downlinks for maybe a few hours a week

Since we are interested in $\nu < 10^{-4}$Hz, requiring a sample of $\Delta\phi$ every ~ hour, actually might only need to send 10 kbps for just an hour each year to get relevant data back!

Other science

Measuring cosmological distances geometrically from outer solar system

The Astrophysical Journal Letters, 947:L23 (20pp), 2023 April 20 https://doi.org/10.3847/2041-8213/acc947

Solar System-scale Interferometry on Fast Radio Bursts Could Measure Cosmic Distances with Subpercent Precision

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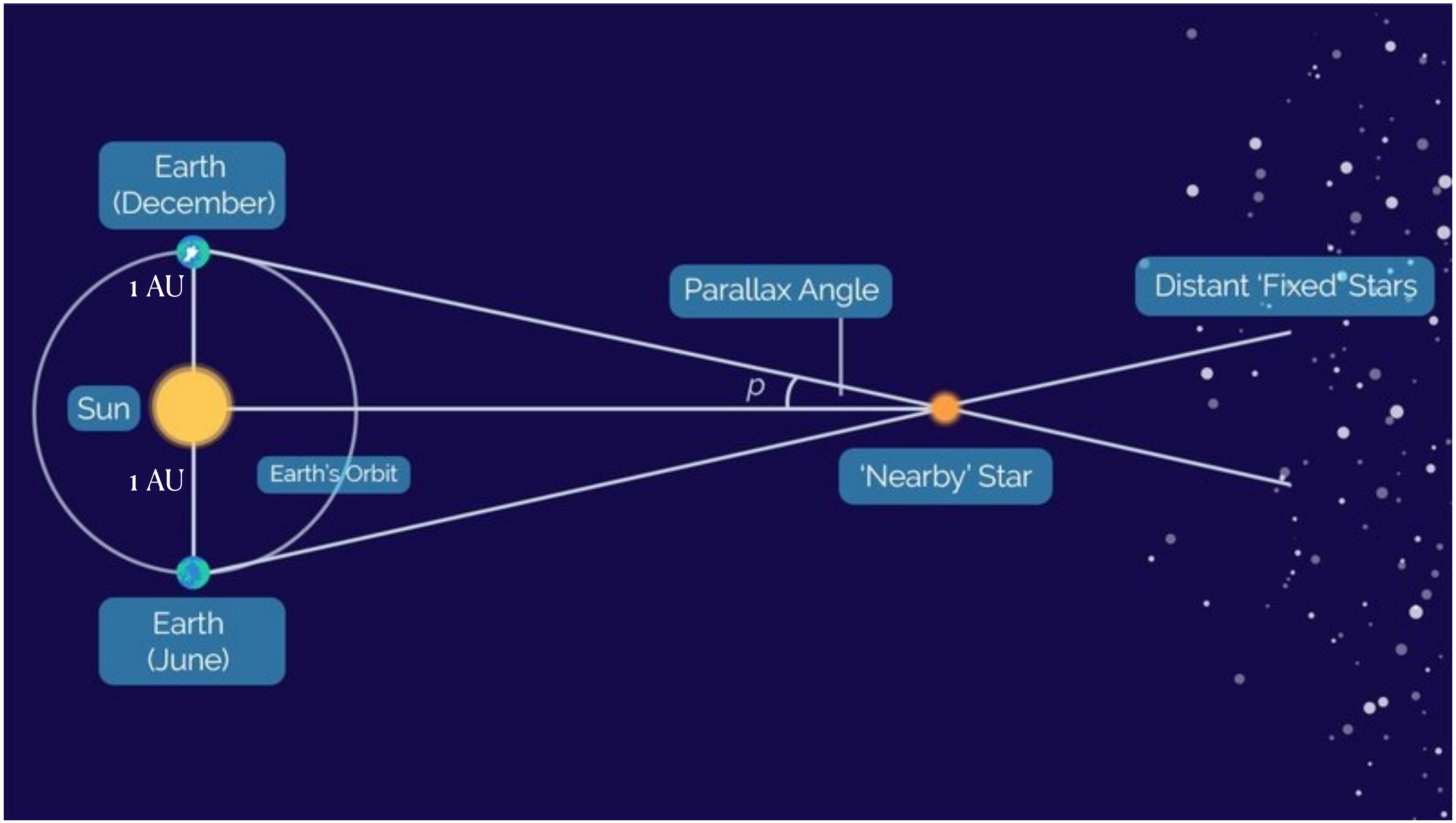
Abstract

The light from an extragalactic source at a distance d will arrive at detectors separated by 100 au at times that differ by as much as $120(d/100\,\mathrm{Mpc})^{-1}$ nanoseconds because of the curvature of the wave front. At gigahertz frequencies, the arrival time difference of a point source can be determined to better than a nanosecond with interferometry. If the spacetime positions of the detectors are known to a few centimeters, comparable to the accuracy to which very long baseline interferometry baselines and global navigation satellite systems (GNSS) geolocations are constrained, nanosecond timing would allow competitive cosmological constraints. We show that a four-detector constellation at Solar radii of $\gtrsim$10 au could measure geometric distances to individual sources with subpercent precision. The precision increases quadratically with baseline length. Fast radio bursts (FRBs) are the only known bright extragalactic radio source that are sufficiently point-like for this experiment, and the simplest approach would target the population of repeating FRBs. Galactic scattering limits the timing precision at $\lesssim$3 GHz, whereas at higher frequencies the precision is set by removing the differential dispersion between the detectors. Furthermore, for baselines greater than 100 au, Shapiro time delays limit the precision, but their effect can be cleaned at the cost of two additional detectors. Outer solar system accelerations that result in $\sim$1 cm uncertainty in detector positions could be corrected for with weekly GNSS-like trilaterations between members of the constellation. The proposed interferometer would not only provide a geometric constraint on the Hubble constant, but also could advance solar system, pulsar, and gravitational wave science.

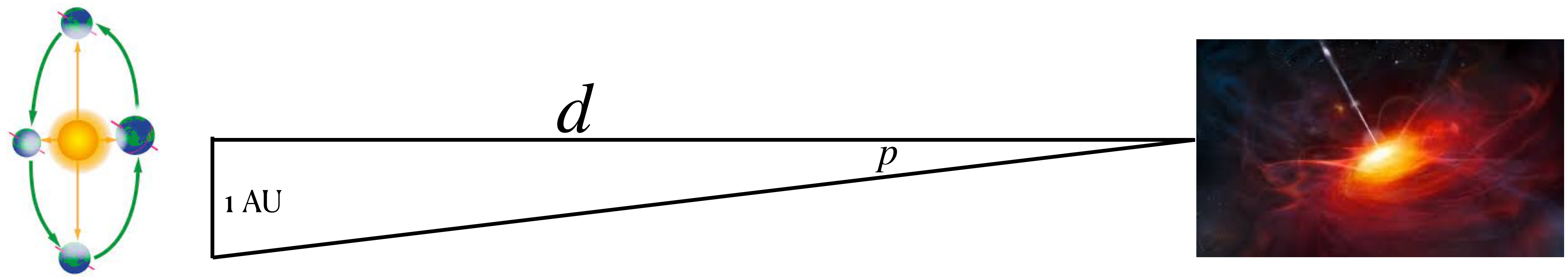
Unified Astronomy Thesaurus concepts: Cosmology (343); Cosmological constant experiments (335); Cosmological parameters (339)

The gold standard for measuring distance in the Galaxy is annual parallax. What would it take to measure parallax to extragalactic sources, get H_0, and stop arguing?



The Gaia Satellite can measure parallaxes to d=10 kpc, but to measure distances for H_0 need to do this for d>100 Mpc because of velocities from local gravitational potentials.

Is parallax over cosmological distances possible?



$$p = \frac{1\mathrm{AU}}{d} = 0.005\left(\frac{200\mathrm{Mpc}}{d}\right)\ \mu-\mathrm{arcsecond}$$

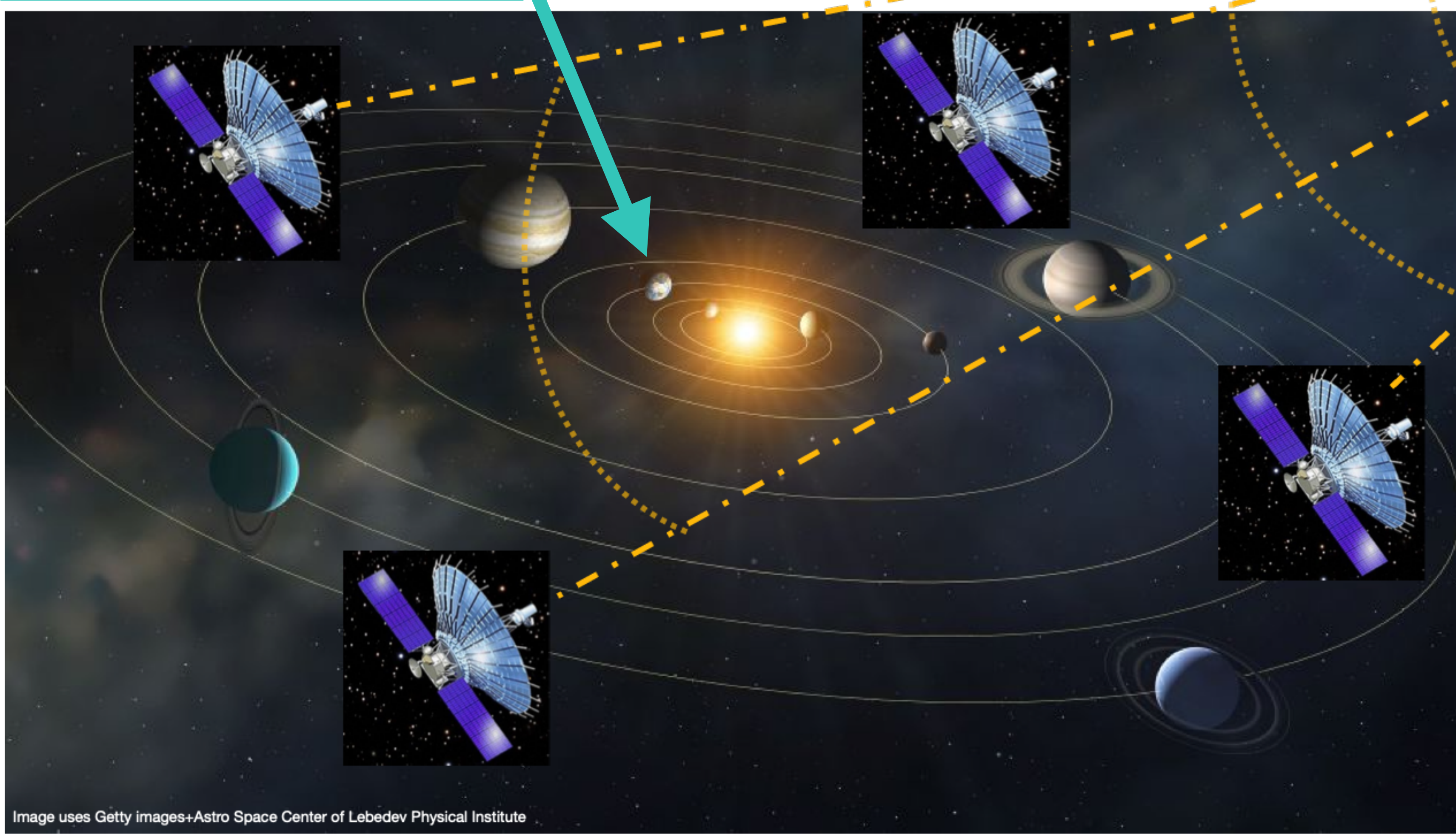
- This is ten thousands times smaller p then Gaia measures
- What would it take to resolve these angles? If observing in radio at wavelength λ then the centroiding of a telescope of size x is

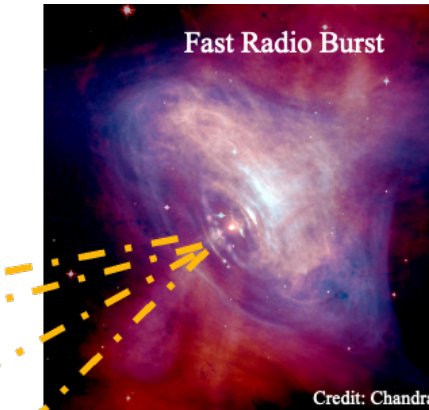
$$\delta p \sim \frac{\lambda}{x\ \mathrm{SNR}} = 0.007\ \frac{1\ \mathrm{AU}}{x}\frac{\lambda}{5\mathrm{cm}}\frac{10}{\mathrm{SNR}}\ \mu-\mathrm{arcsecond}$$

Just **need an AU-sized telescope (e.g. baseline) and can detect this!**

Basic picture

Ground station support:
get high S/N voltage template to
pull satellite signal out of noise

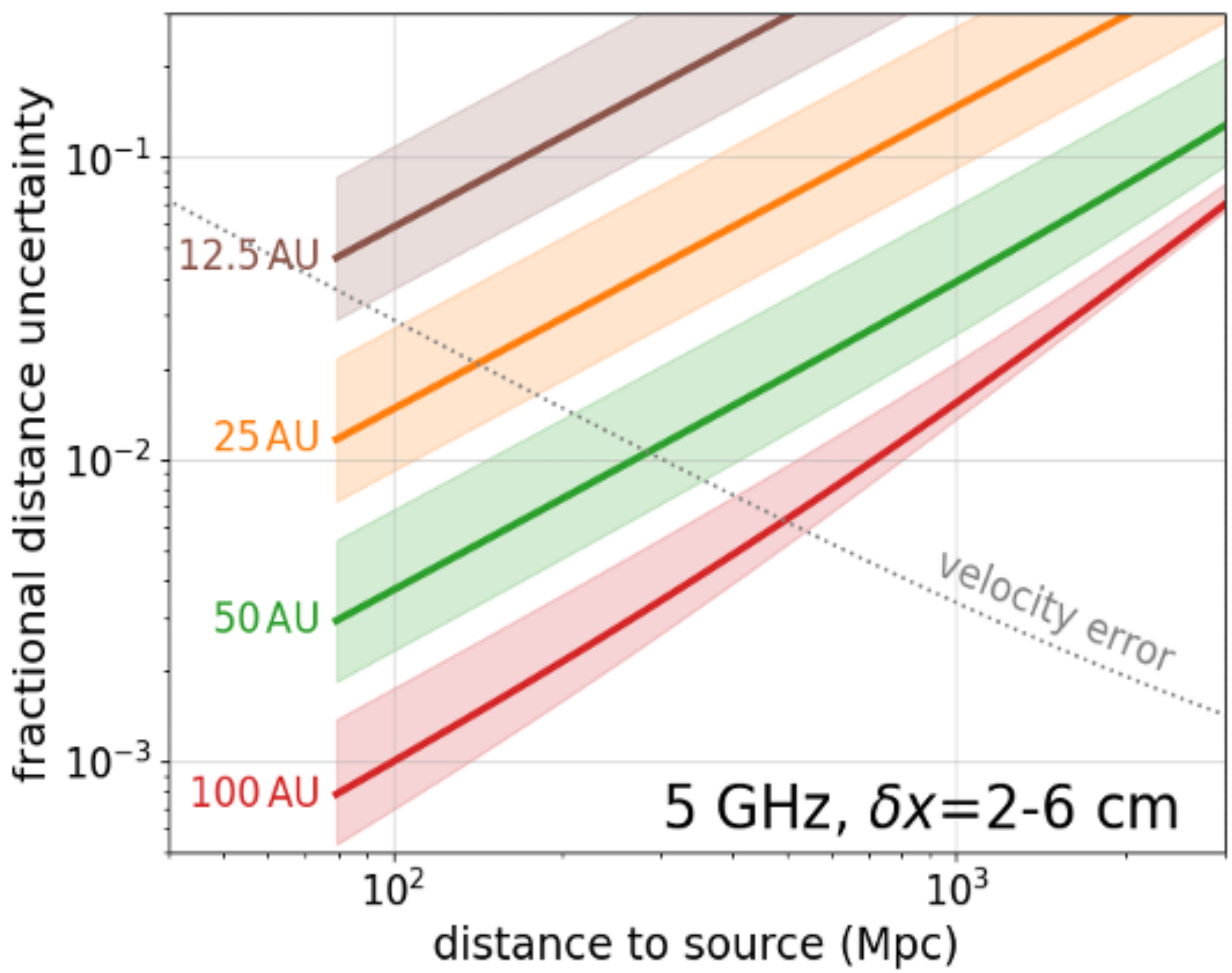




FRBs are Goldilocks source:
They can be quite bright (> Jy) and so detectable with a small dish, they last less than a millisecond so voltage time series can be downlinked, they are a point source, they are at the ideal distances, some repeat and so we know where to point.

GPS-like measurement of distance from curvature of wavefront

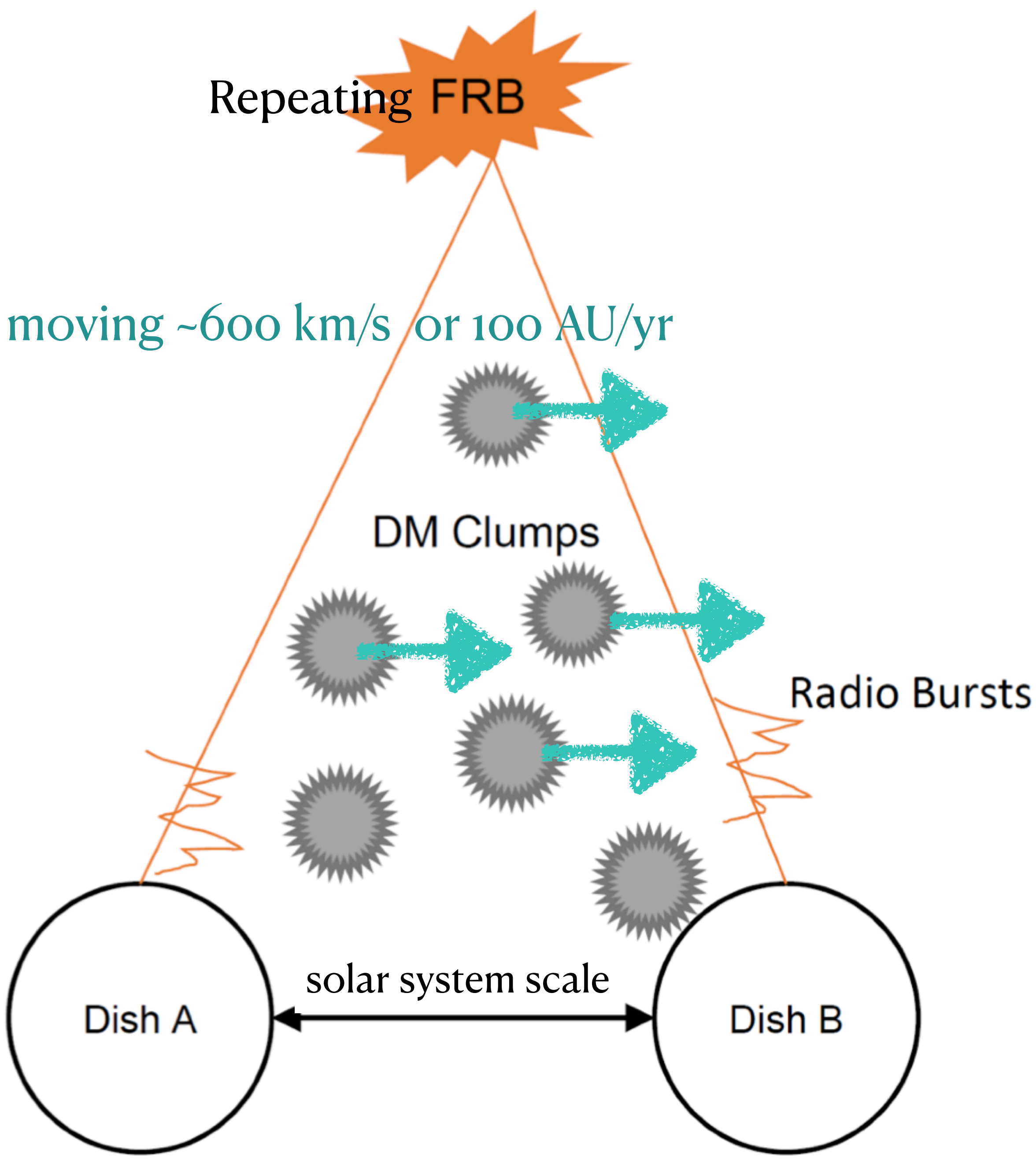
Preliminary forecasts for how well distances could be constrained *to a single FRB*

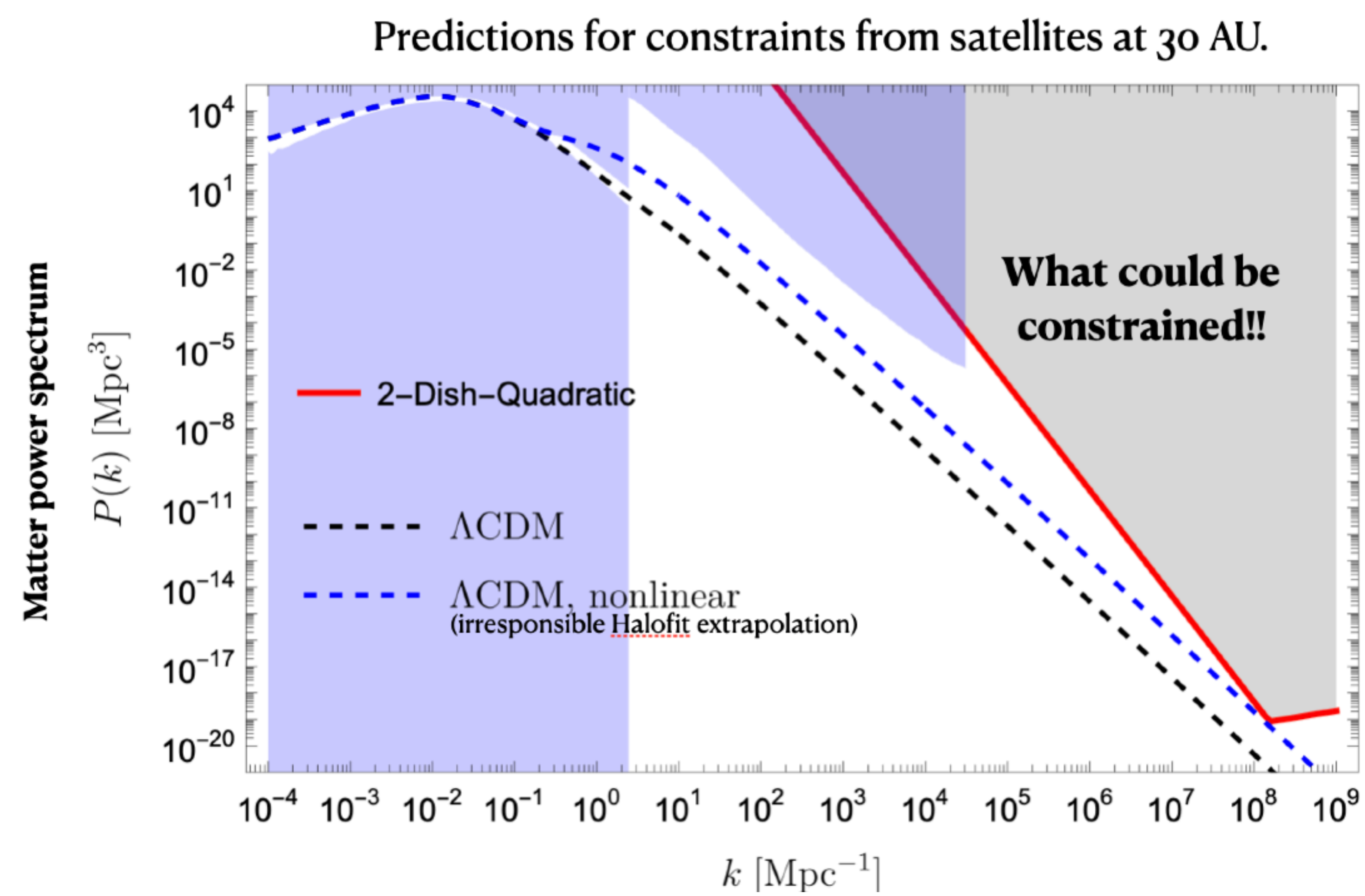


Width of bands reflects range of detector positional errors δx.
Curves assume 20% fractional bandwidth and SNR=5 on each baseline.

Anything else radio dishes on other sides of Solar System can do?

Dark matter clumpiness on sub-solar mass scales

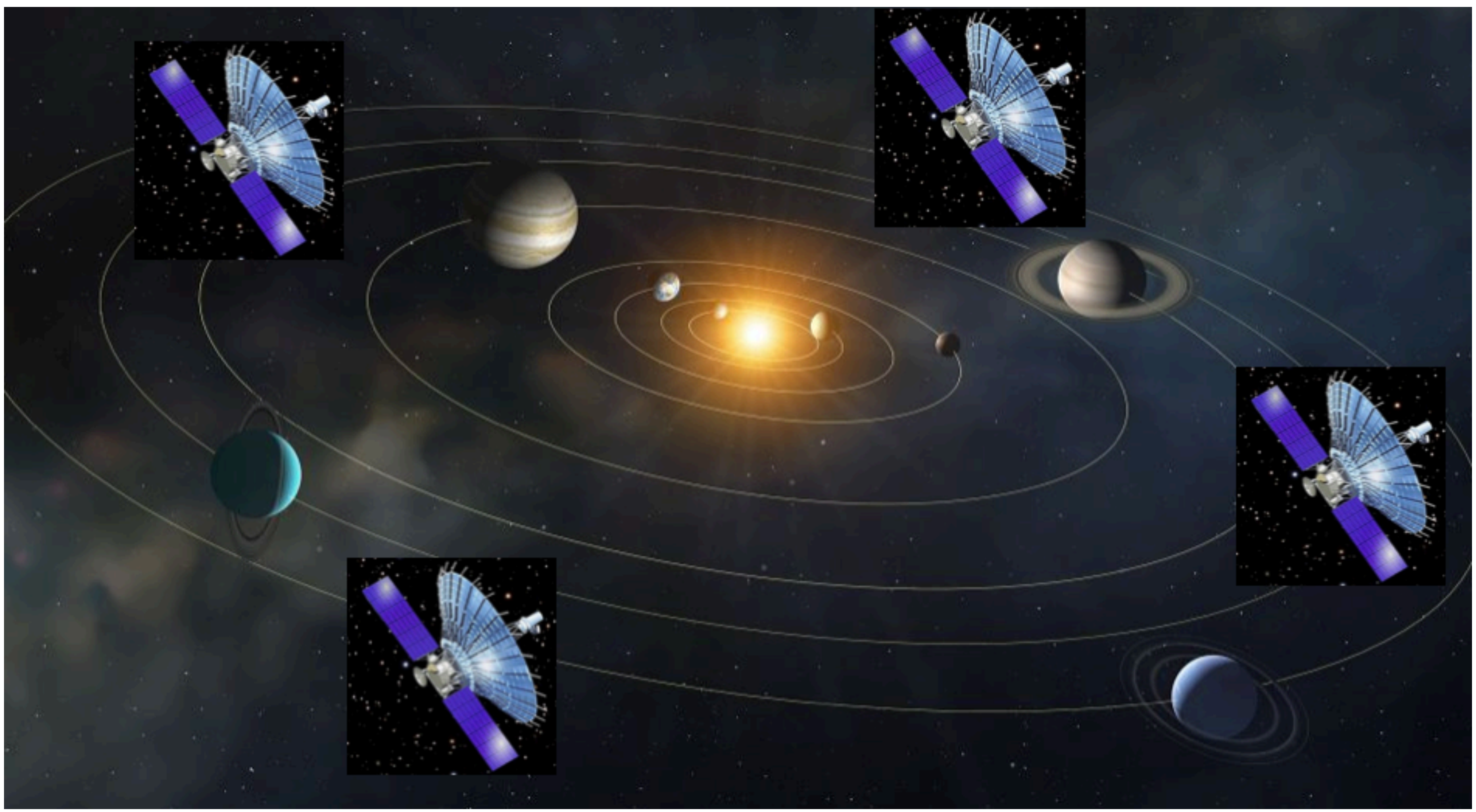




Xiao, Dai, & McQuinn arXiv:2401.08862

Conclusions

I'm hoping you now think radio dishes to the outer Solar System is less crazy than at beginning of my talk :)



PS The next outer Solar System probe doesn't have to explore Uranus.