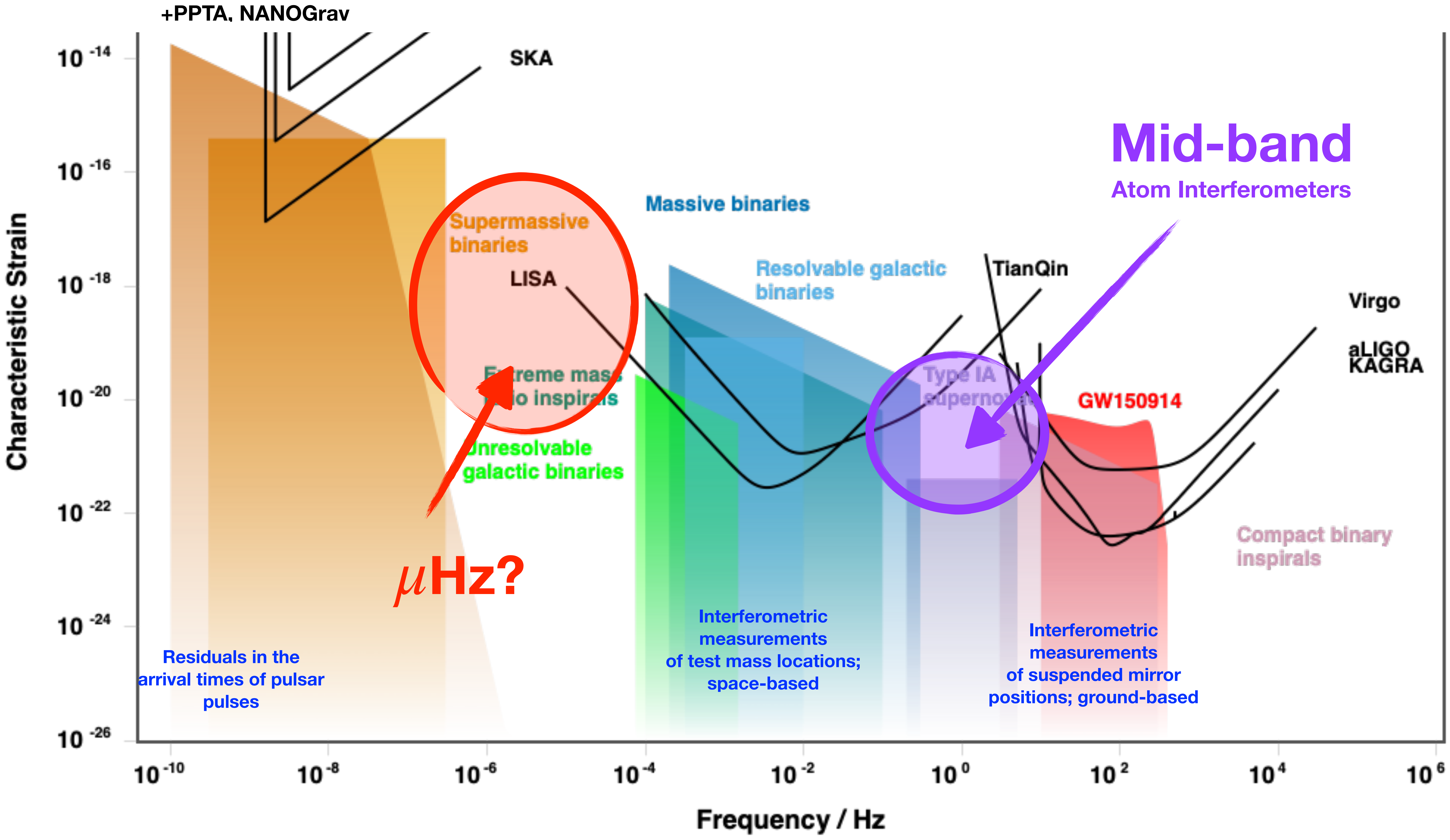
Gravitational Wave Detection between NANOGRAV and LISA

Surjeet Rajendran
The Johns Hopkins University

The Gravitational Wave Spectrum

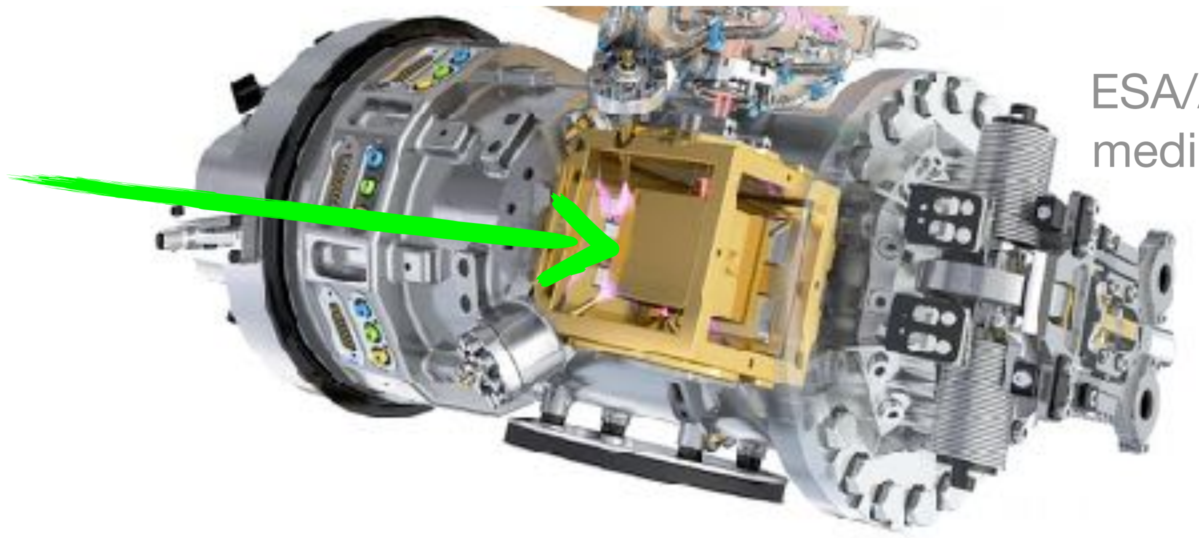


Stability

Precision

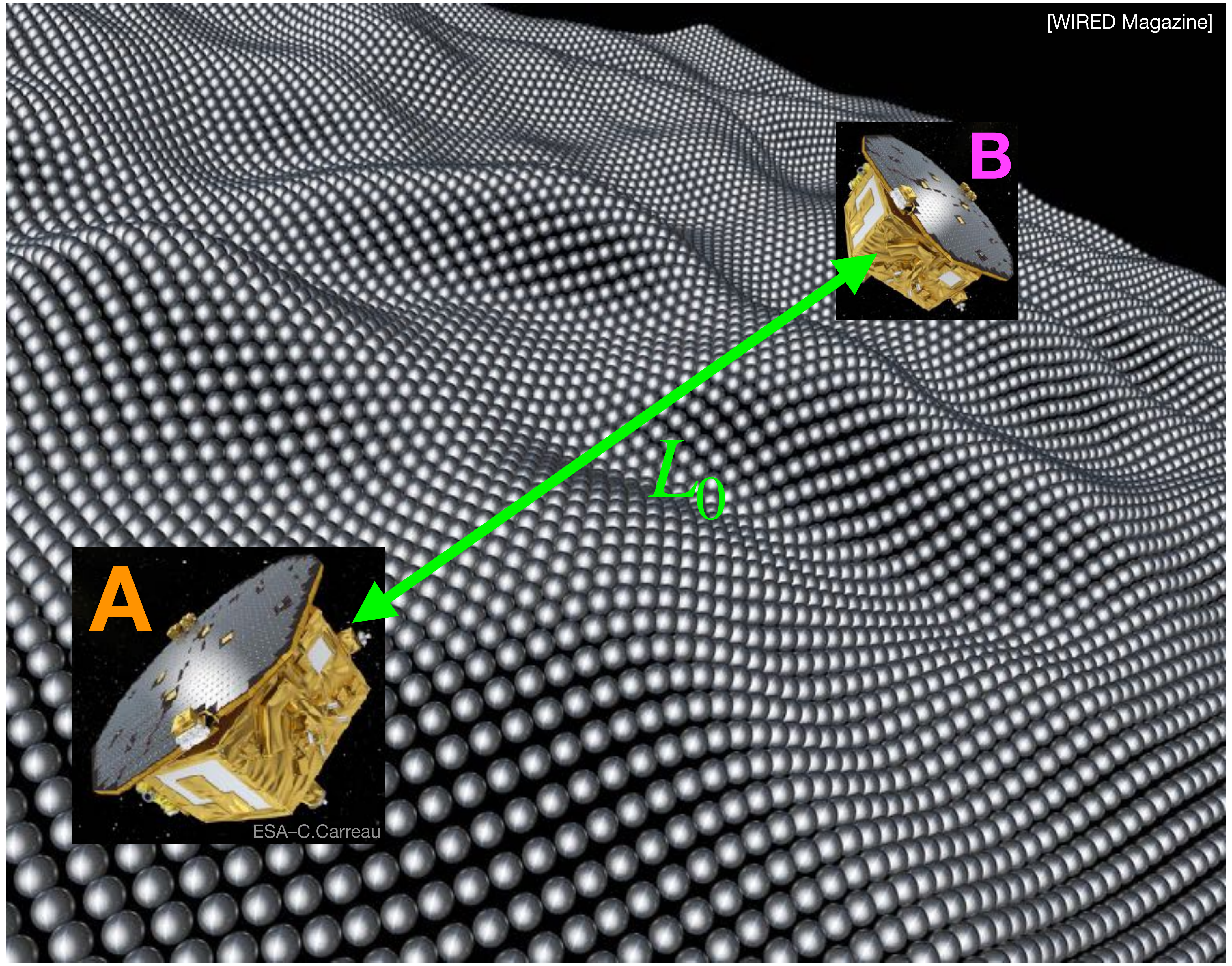
Local Test Mass based GW Detection 101

Satellites with drag-free test masses (TM)



ESA/ATG medialab

Light travel time (= proper distance) between test masses is modulated by GW



Emitter (A) sends pulse at $t_A = t_0$;
receiver (B) gets pulse at $t_B = t_0 + \Delta t$:

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

GW strain amplitude

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

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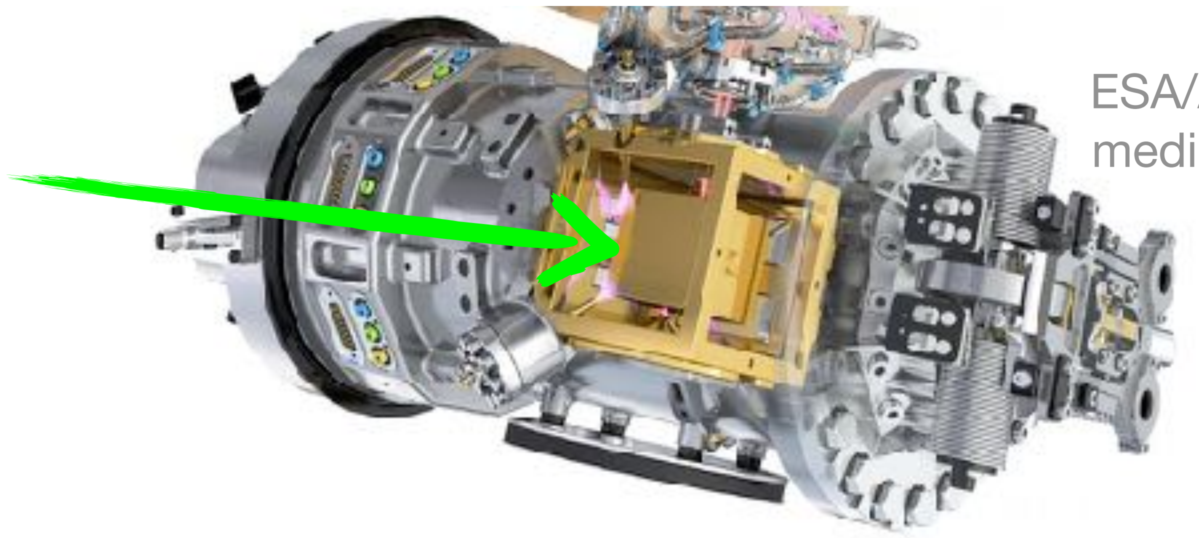

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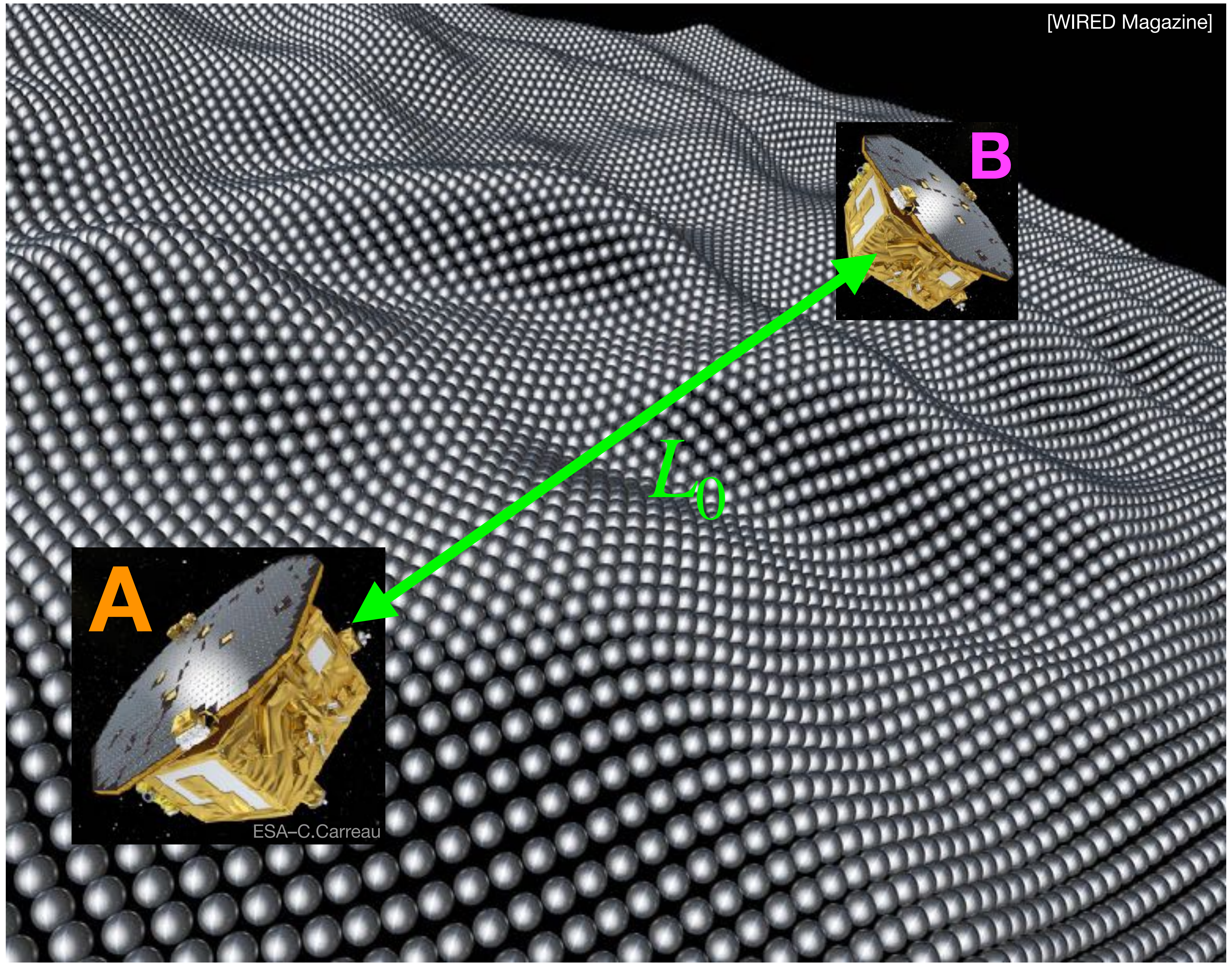

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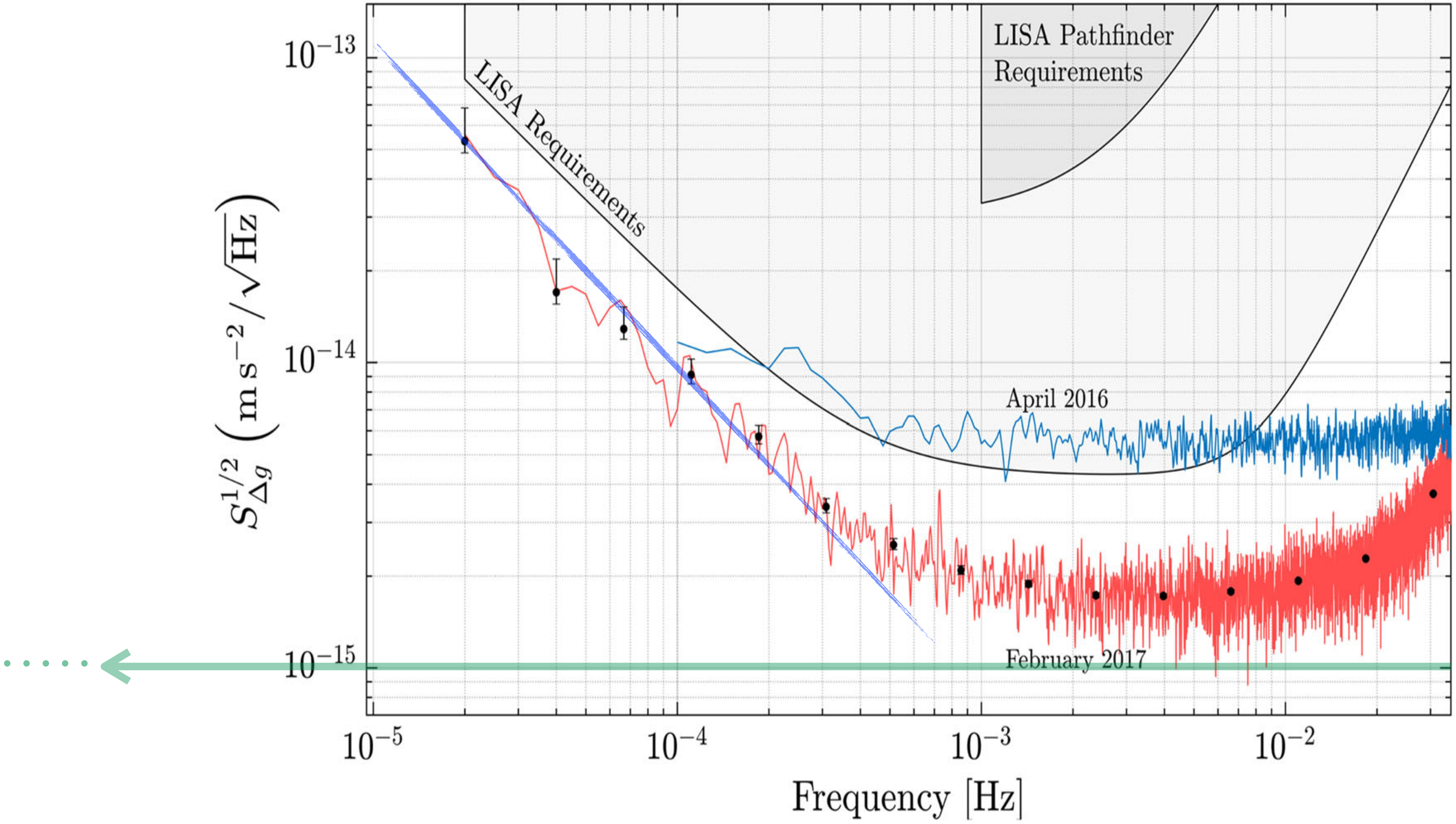
How drag free?

LISA Pathfinder Results

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



LISA Pathfinder

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

[Phys. Rev. Lett. **120**, 061101 (2018)]

Mission Concept

Suppress acceleration noise by having very large test mass

$$a = \frac{F}{M}$$

How do we launch?

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Planets?

Stable Center of Mass
Unstable Surface: Seismics/
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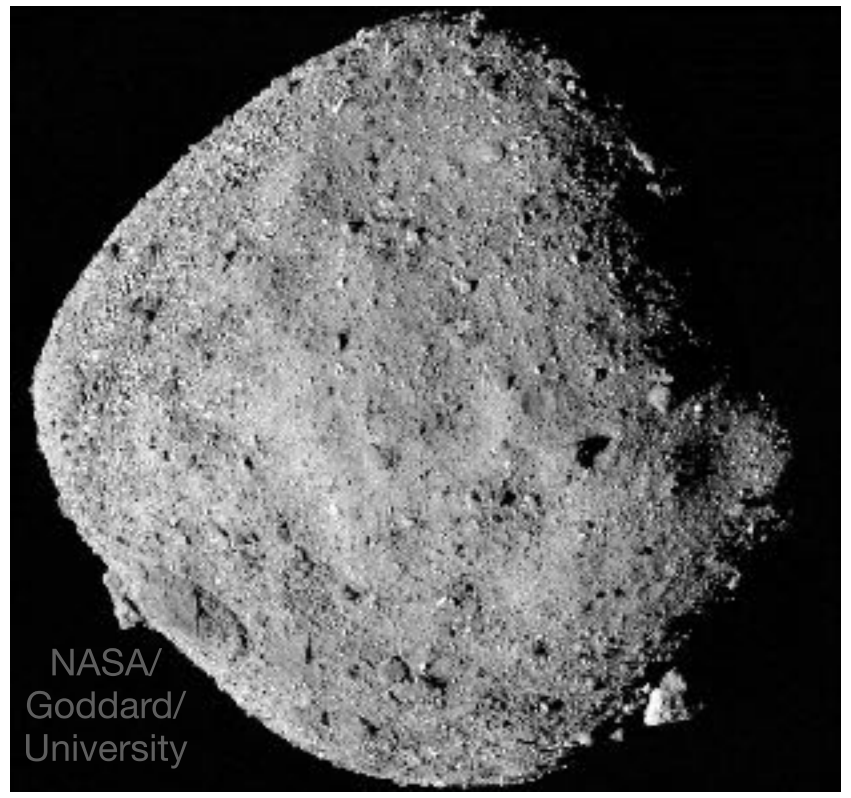
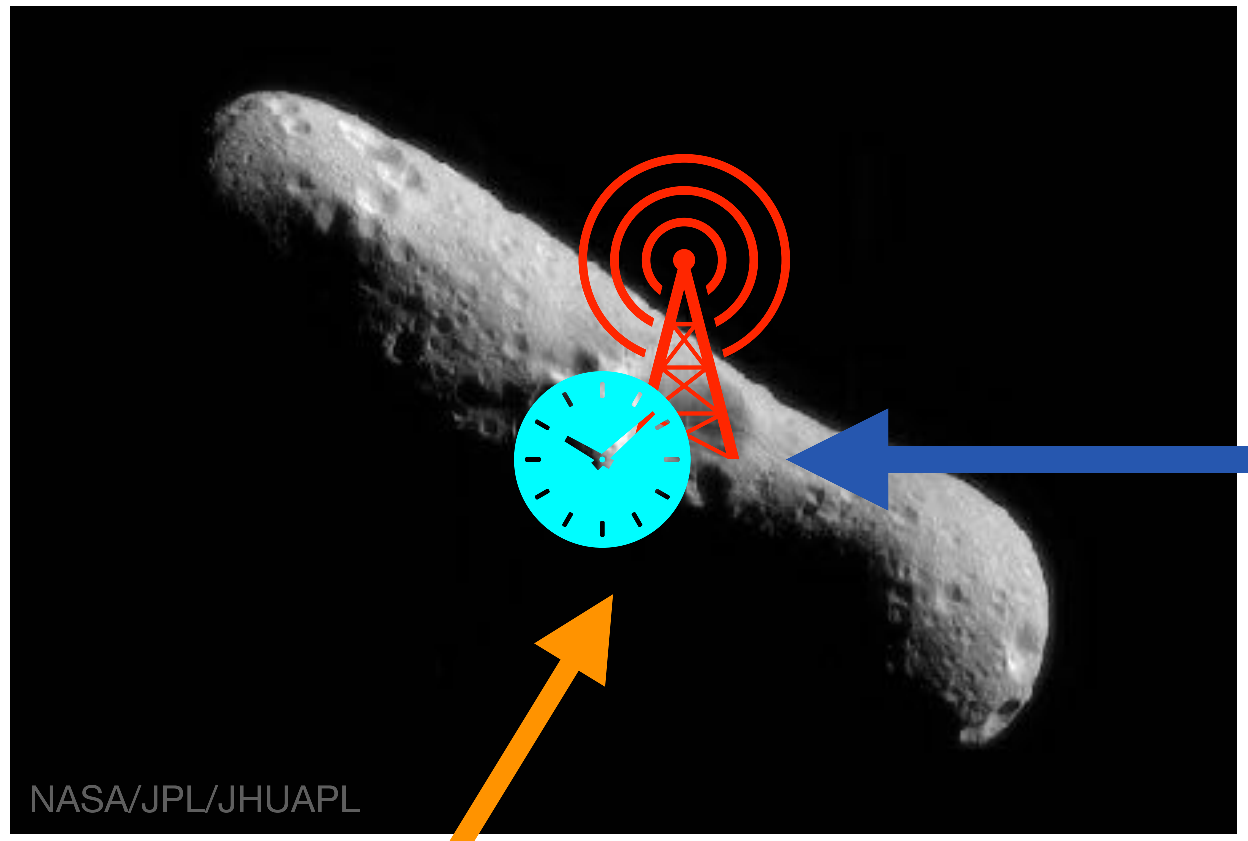


Asteroids?

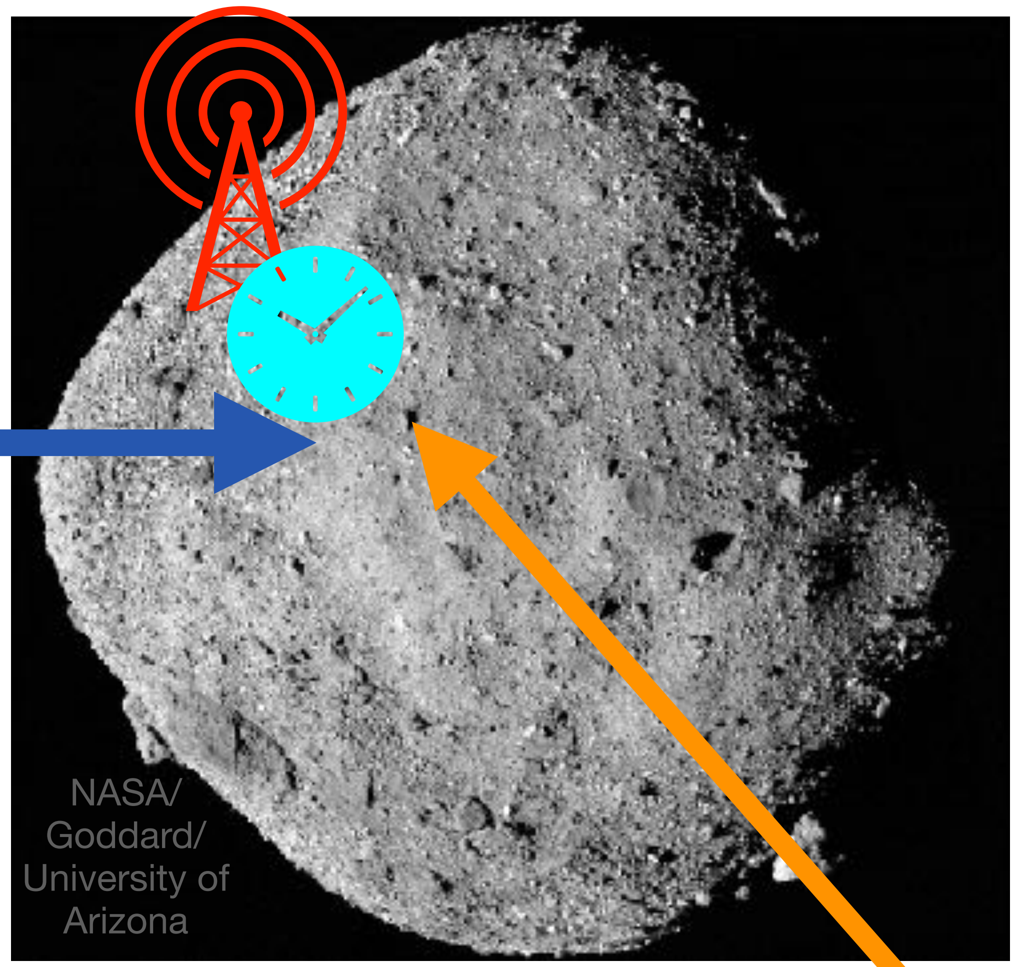
Few km scale rocks

Mission Concept

Mission Concept



Radio/Laser Range



Deployed base station

Deployed base station

Stability?

$$h \sim 10^{-17} - 10^{-18}, L \sim 1 \text{ AU} \implies \delta x \sim hL \sim 0.1\,\mu\text{m}$$

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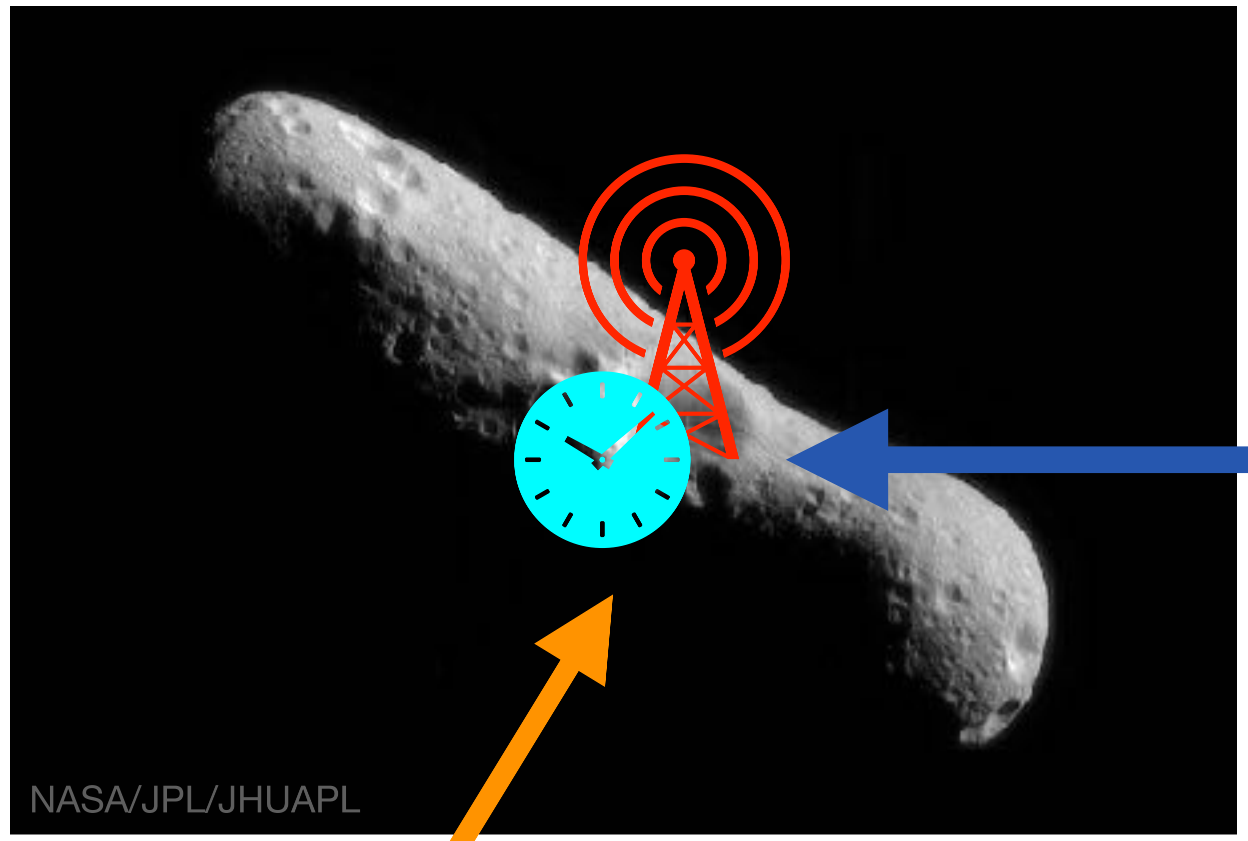

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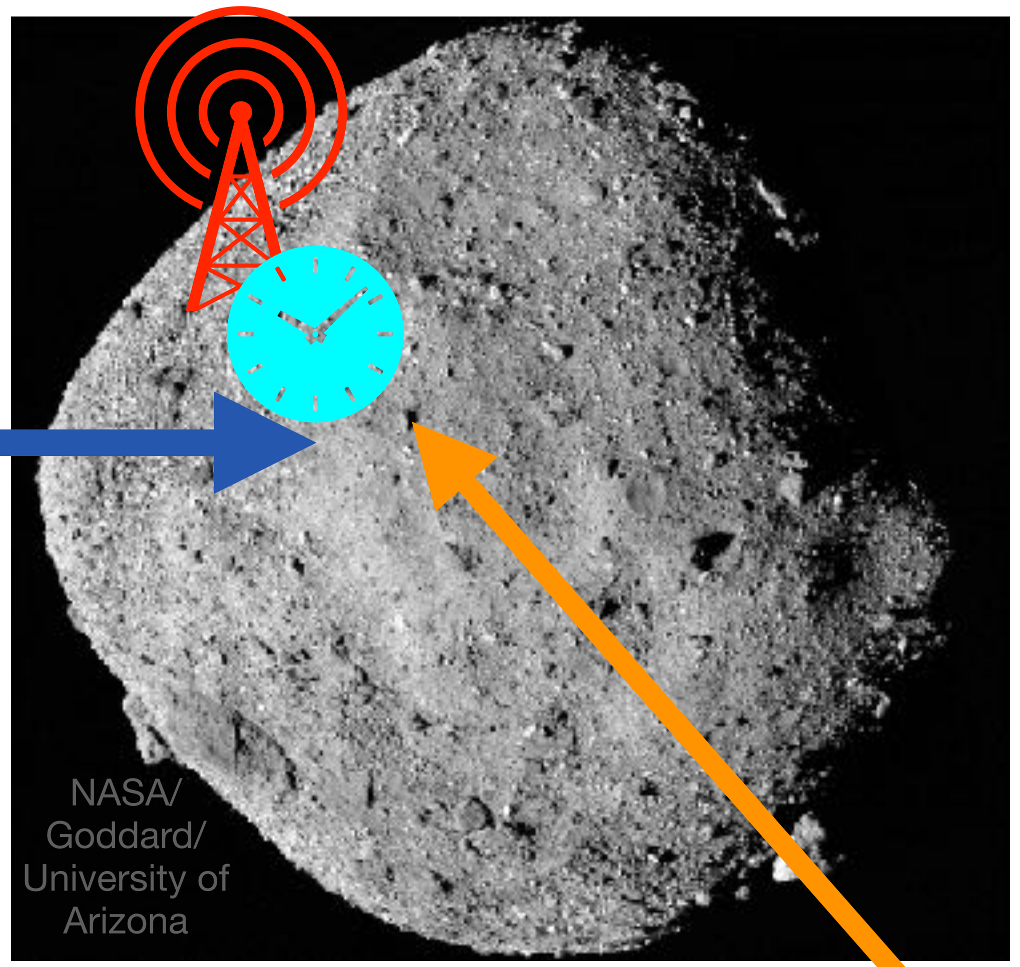

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Land on Asteroids?

Do we have good enough atomic clocks?

Is the asteroid surface/center of mass stable enough?

Noise sources

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

- Solar intensity fluctuations (CoM + torques)
- Solar wind fluctuations (CoM + torques)
- Thermal cycling
- Noise at rotational period
- Gravity Gradient Noise from other $\sim 10^6$ asteroids in Main Belt
- Seismics
- Charging
- Magnetic forces and torques
- Collisions
- Tidal deformation
- etc…

- Clock noise
- Link (shot/thermal) noise

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

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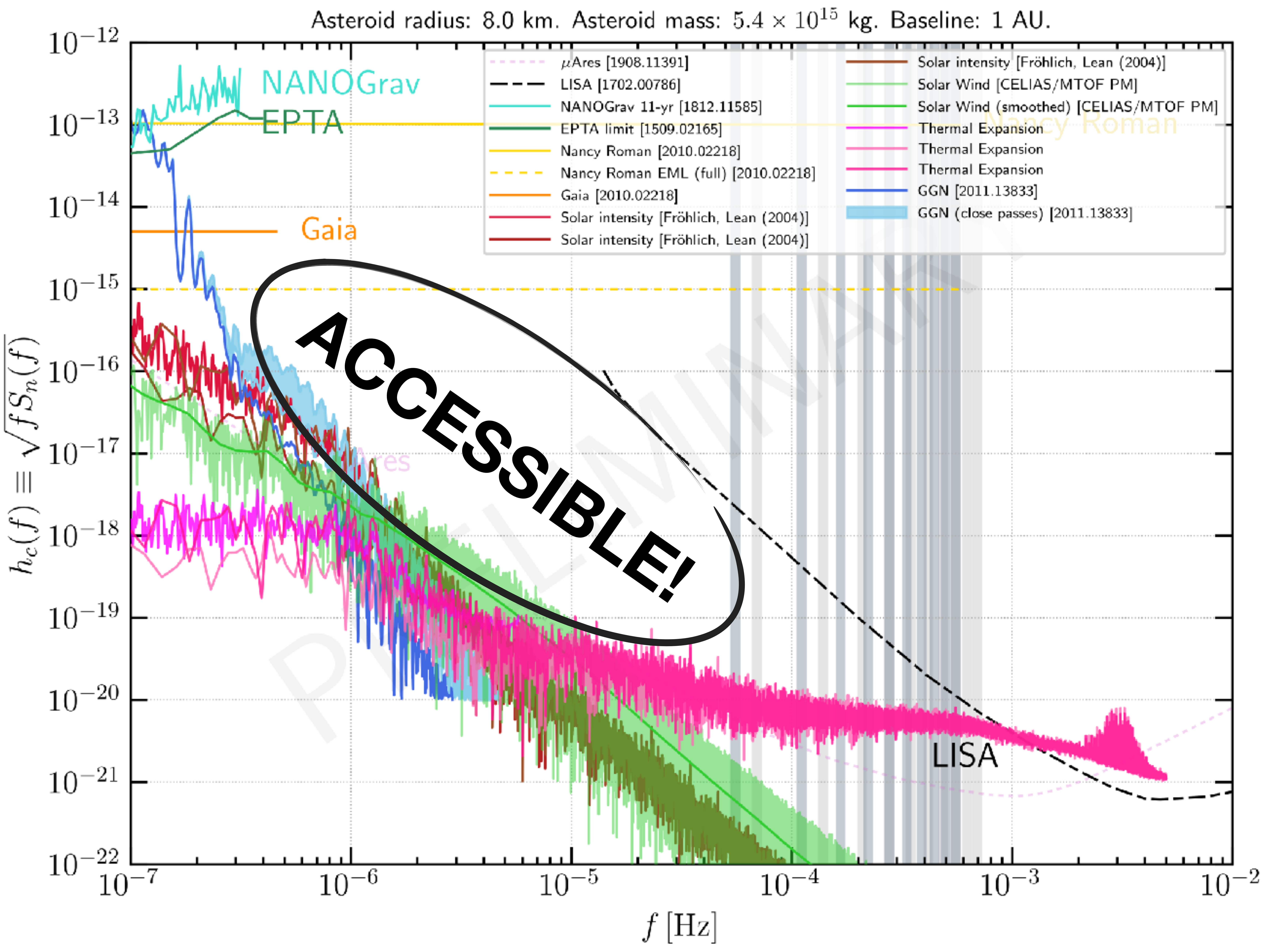
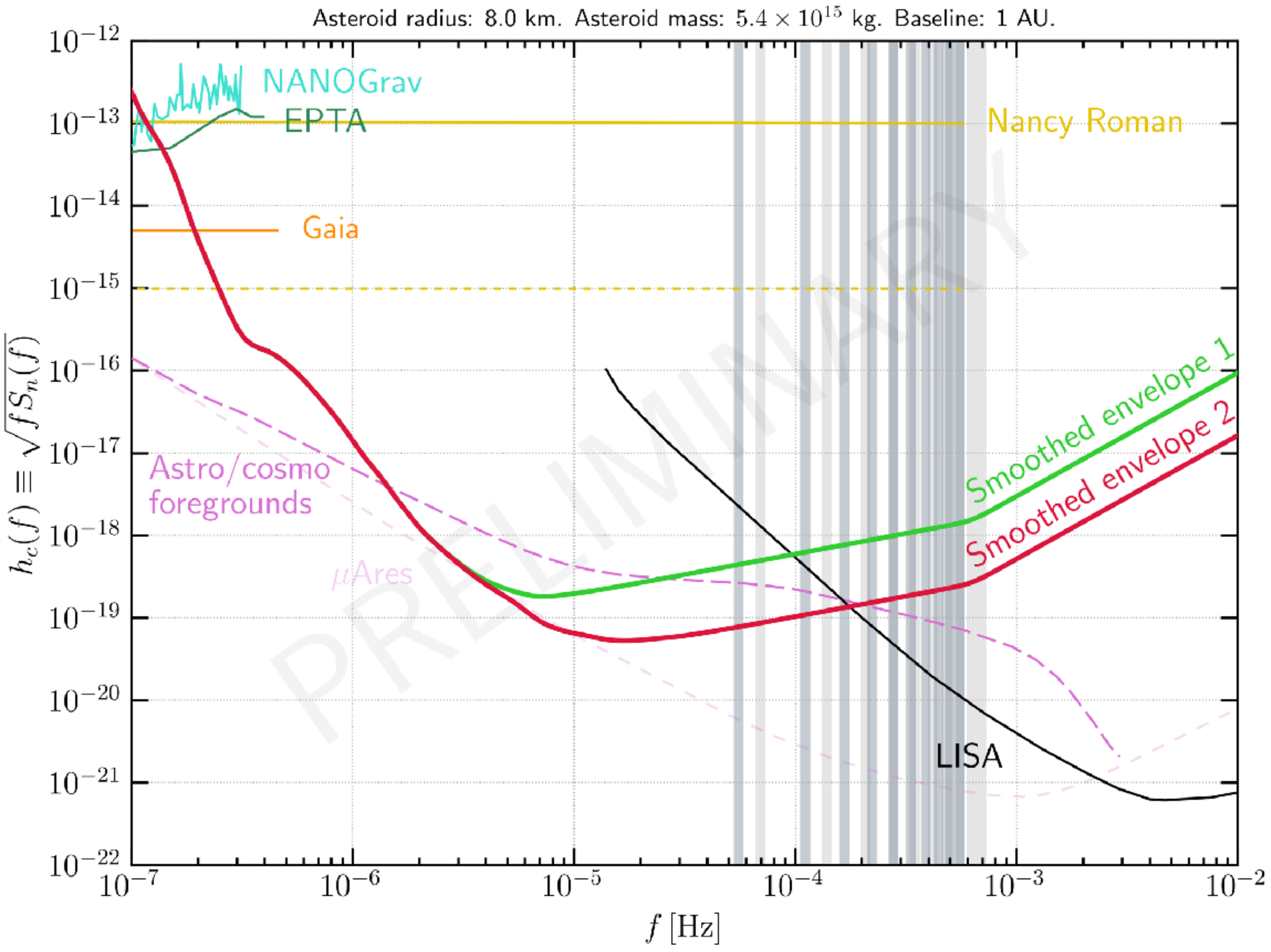


ASTEROIDS ARE EXCELLENT TEST MASSES IN THE μHz BAND!

Projections



Asteroids are excellent test masses for a GW detector in the μHz band

~ m scale laser/radio ranging between on-asteroid base stations equipped with transmit/receive capability and atomic clocks gets excellent sensitivity

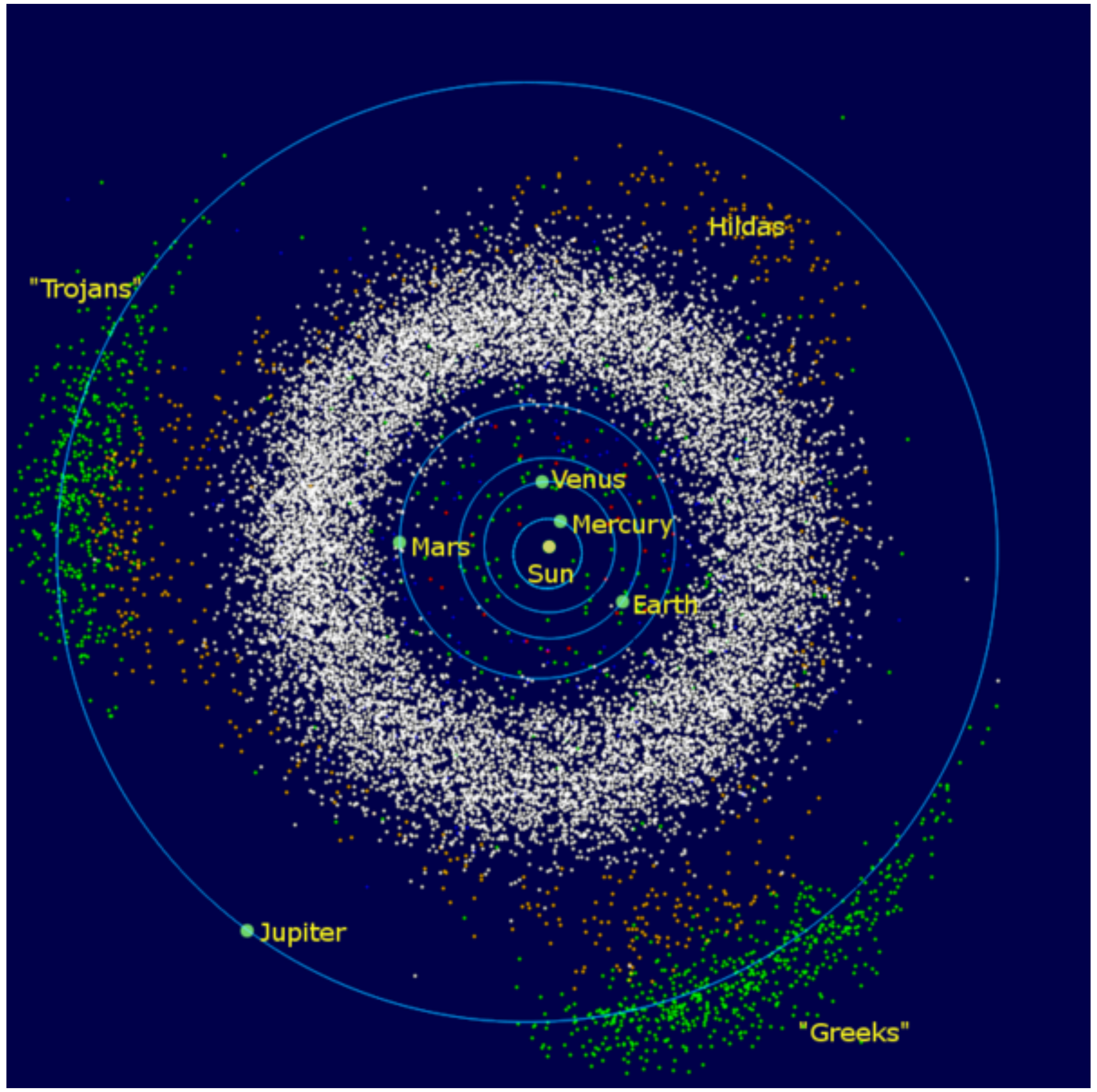
Strongly motivates:

- a detailed technical design study
- in-situ seismic / plastic deformation monitoring of asteroids in upcoming missions
- space-qualifying cold-atom atomic clocks

Astrometry (10 nHz - 1 μHz)

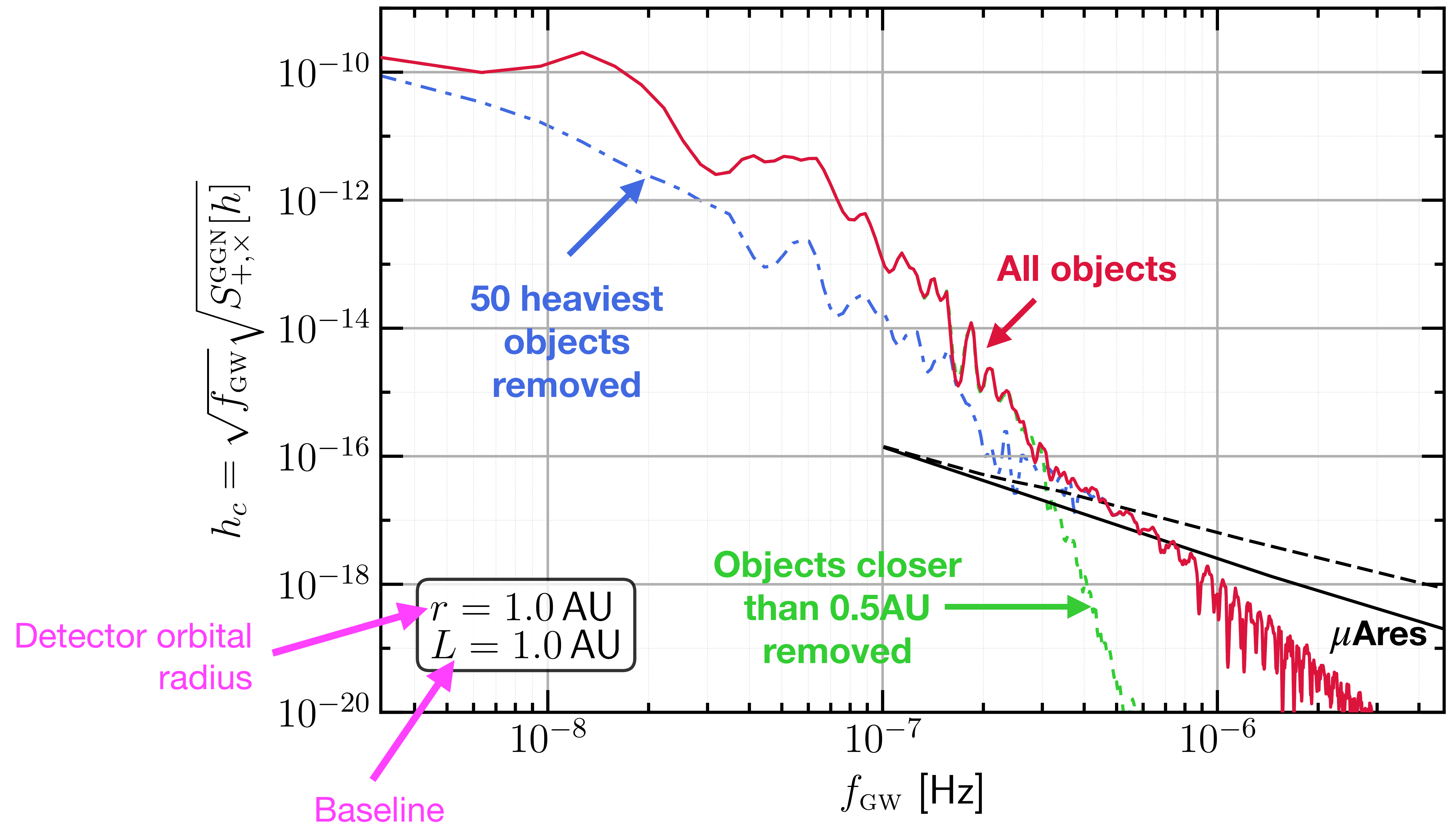
Gravity Gradient Noise below μHz

- The Sun, Planets (and Pluto), Moons
  - Relatively few
  - Masses (or $G_N M$) and locations known
  - **Not** noise (model out)
- The Inner Solar System asteroids
  - $\mathcal{O}(10^6)$ objects
  - *Generally,* masses poorly / indirectly determined
  - Locations are known to some extent
  - **NOT** reasonable to assume that one can successfully model these out
  - Asteroid gravity gradient noise (GGN)!



Gravity Gradient Simulation

- Use NASA JPL Small-Body Database
- 10-year mission simulation
- Detectors on circular orbit @ 1AU; asteroids on elliptical orbits (not N-body)
- Test mass accelerations from asteroids ⟶ "noise" power spectrum (details) ⟶ strain sensitivity.



- Problematic for **ANY** local-test mass-based GW detector with Inner Solar System baselines, up to frequencies ~ $(\text{few}) \times 10^{-7}\,\text{Hz}$
- Removing ~50 heavy distant objects does not change this conclusion
- At higher frequency, noise drops off. But only ~1/6 of objects in database used in simulation: missing diameters for smaller, closer passing objects…

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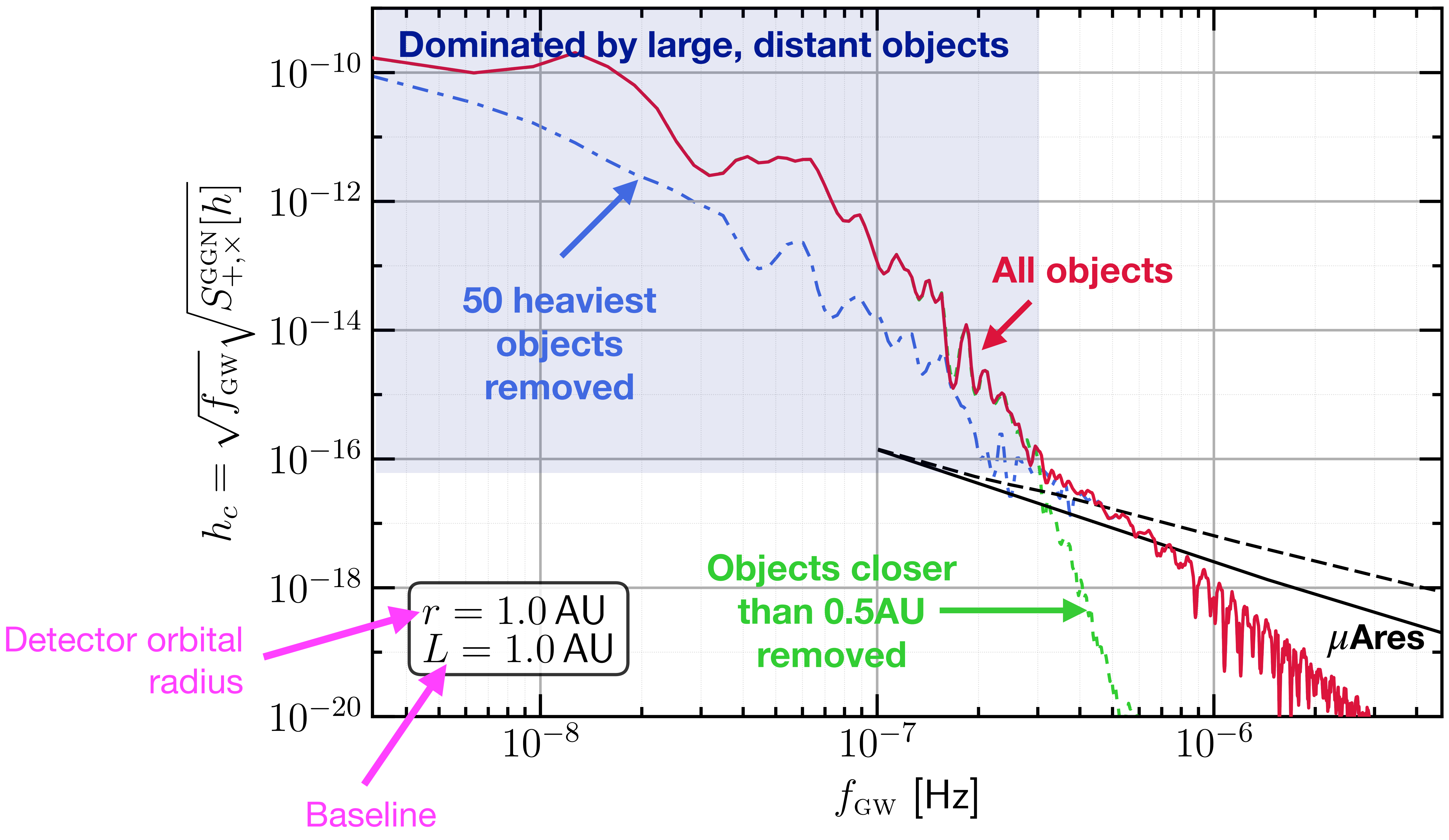

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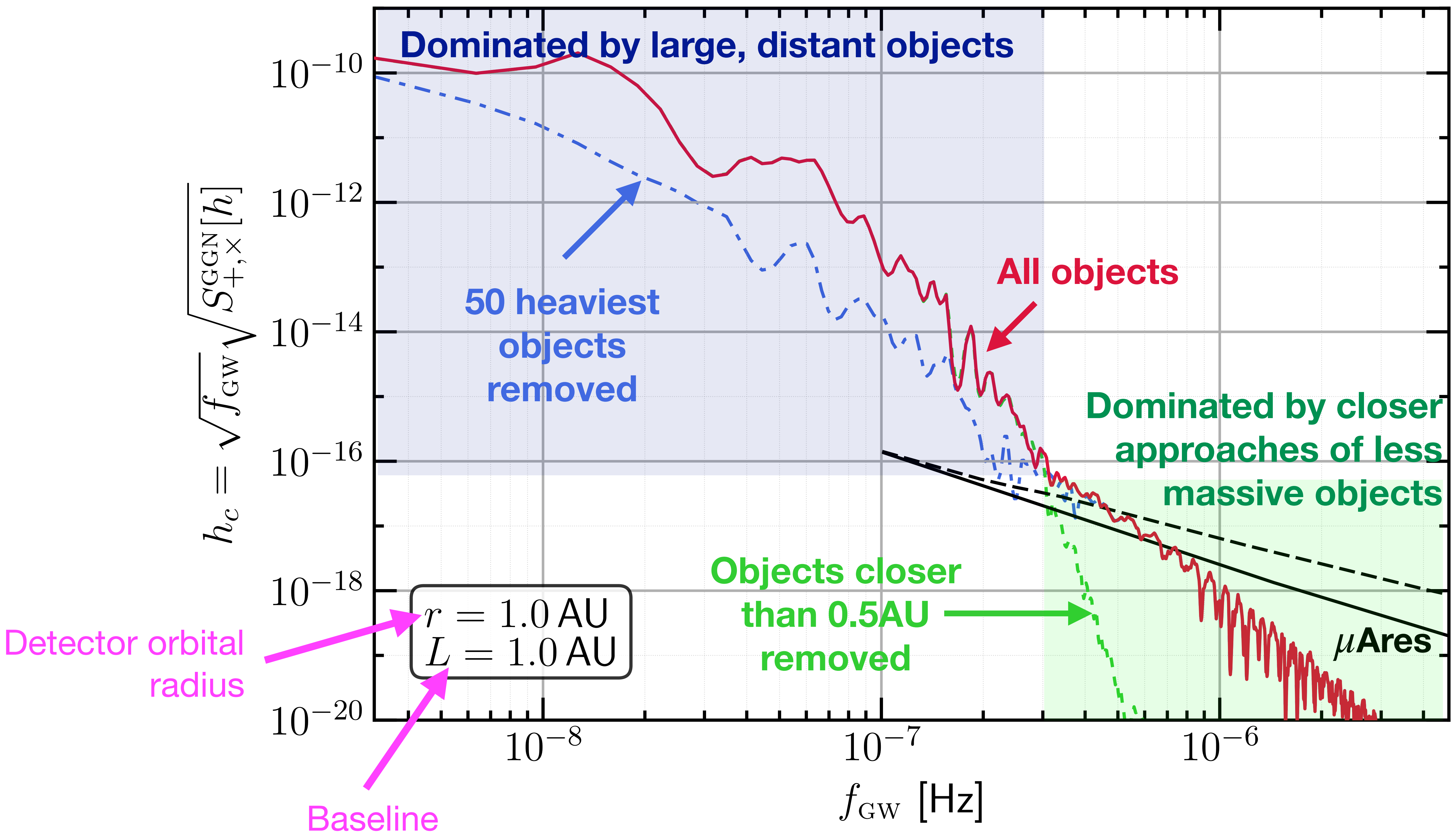

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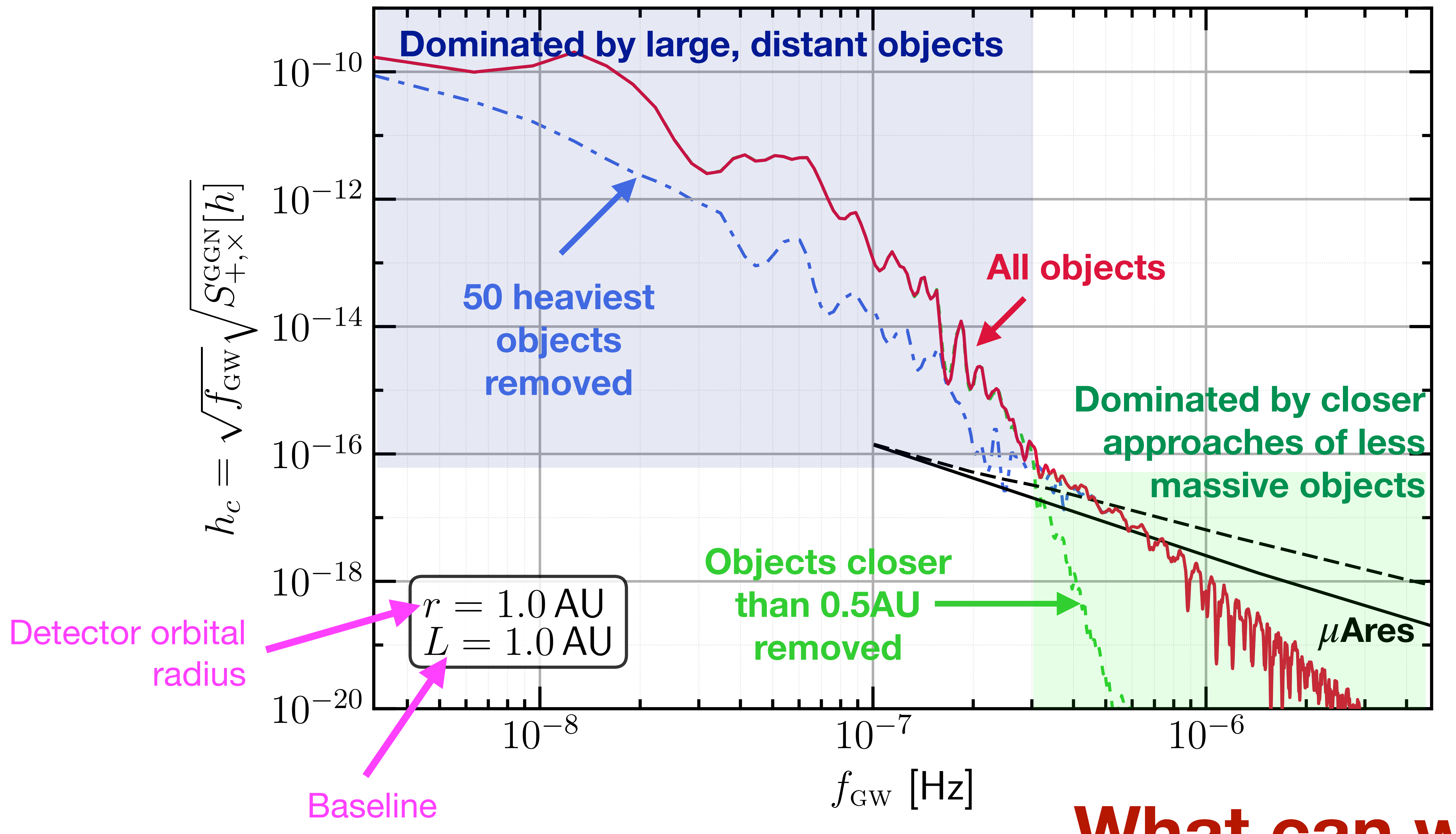

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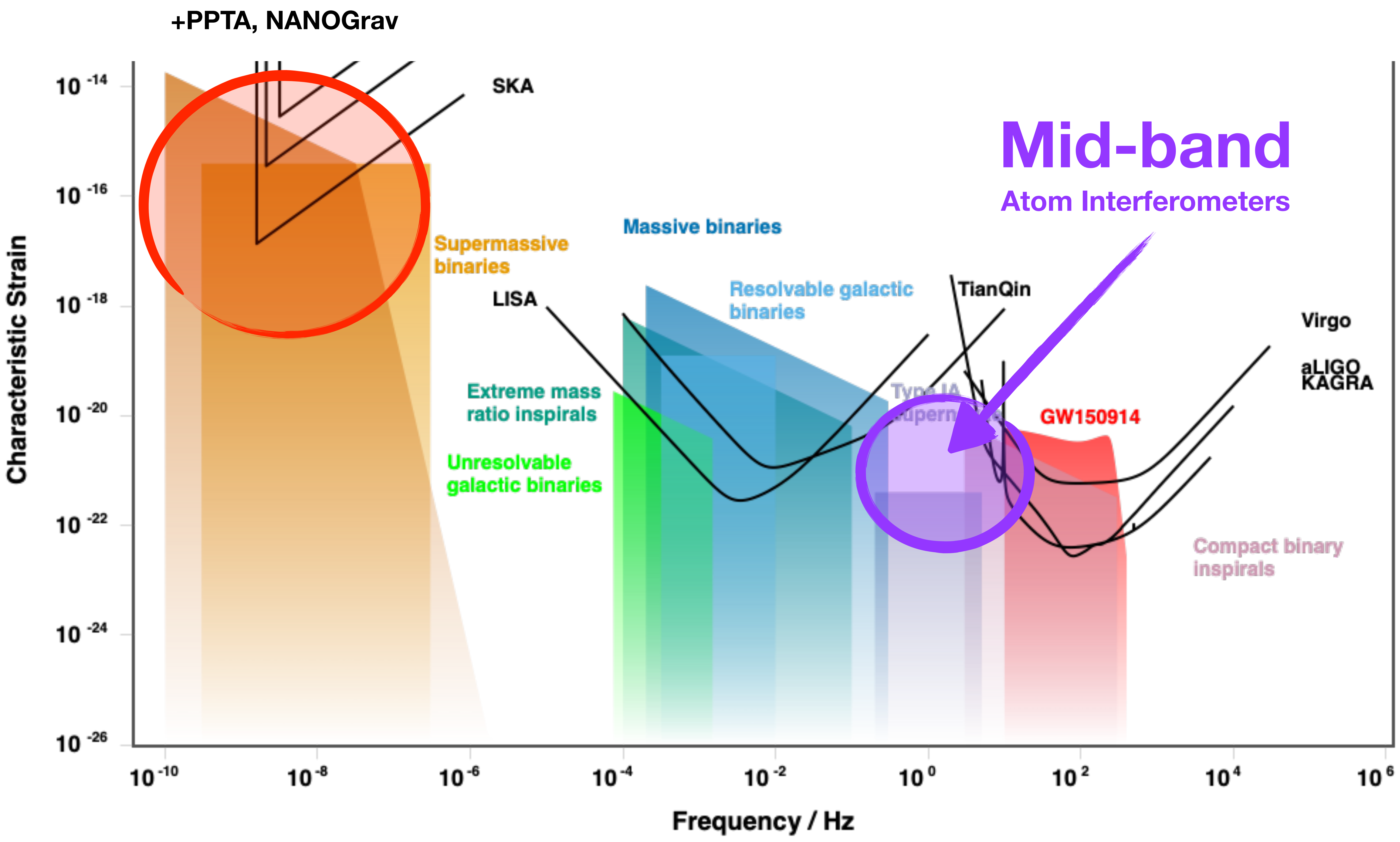
What can we do?

Distant Proof Masses



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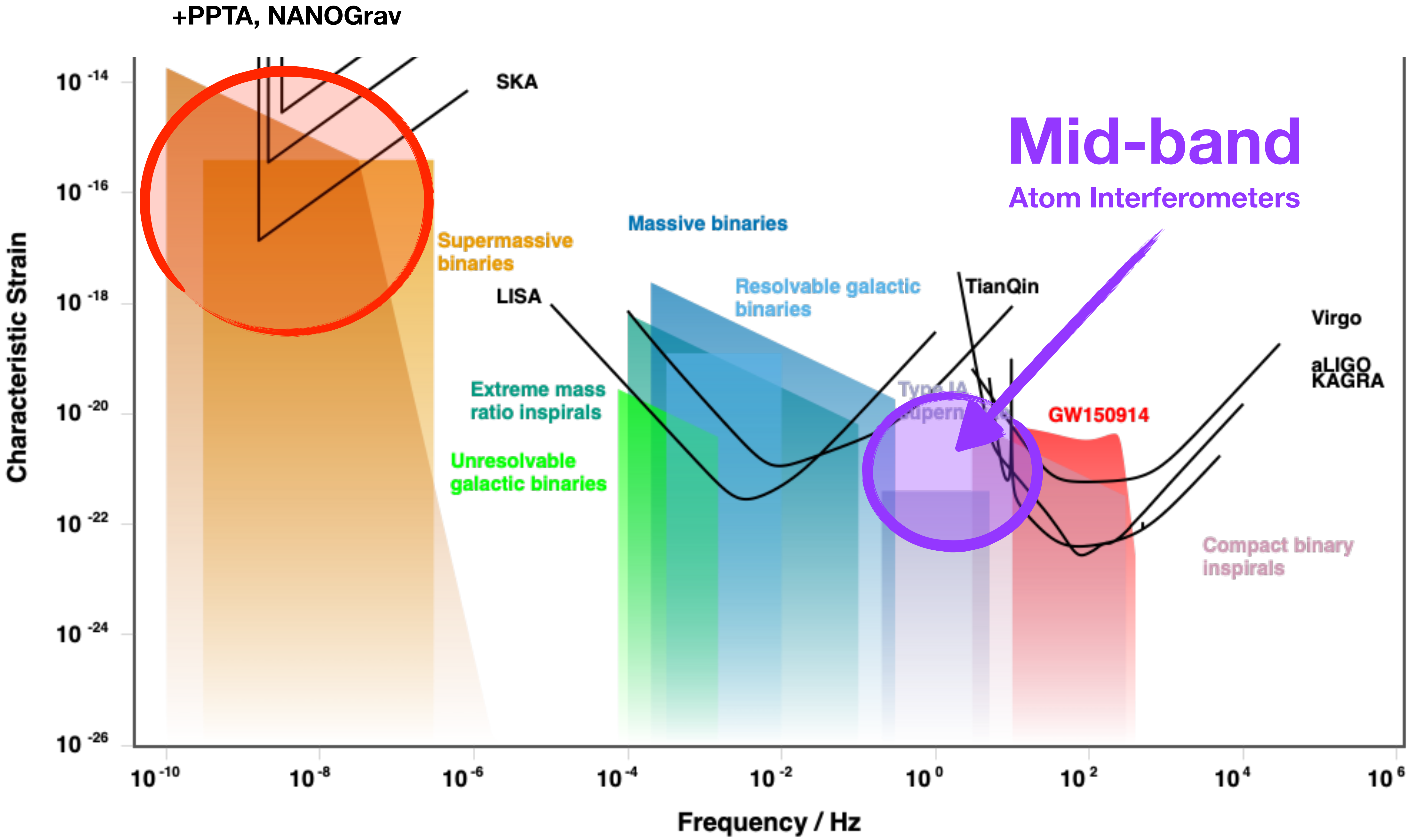
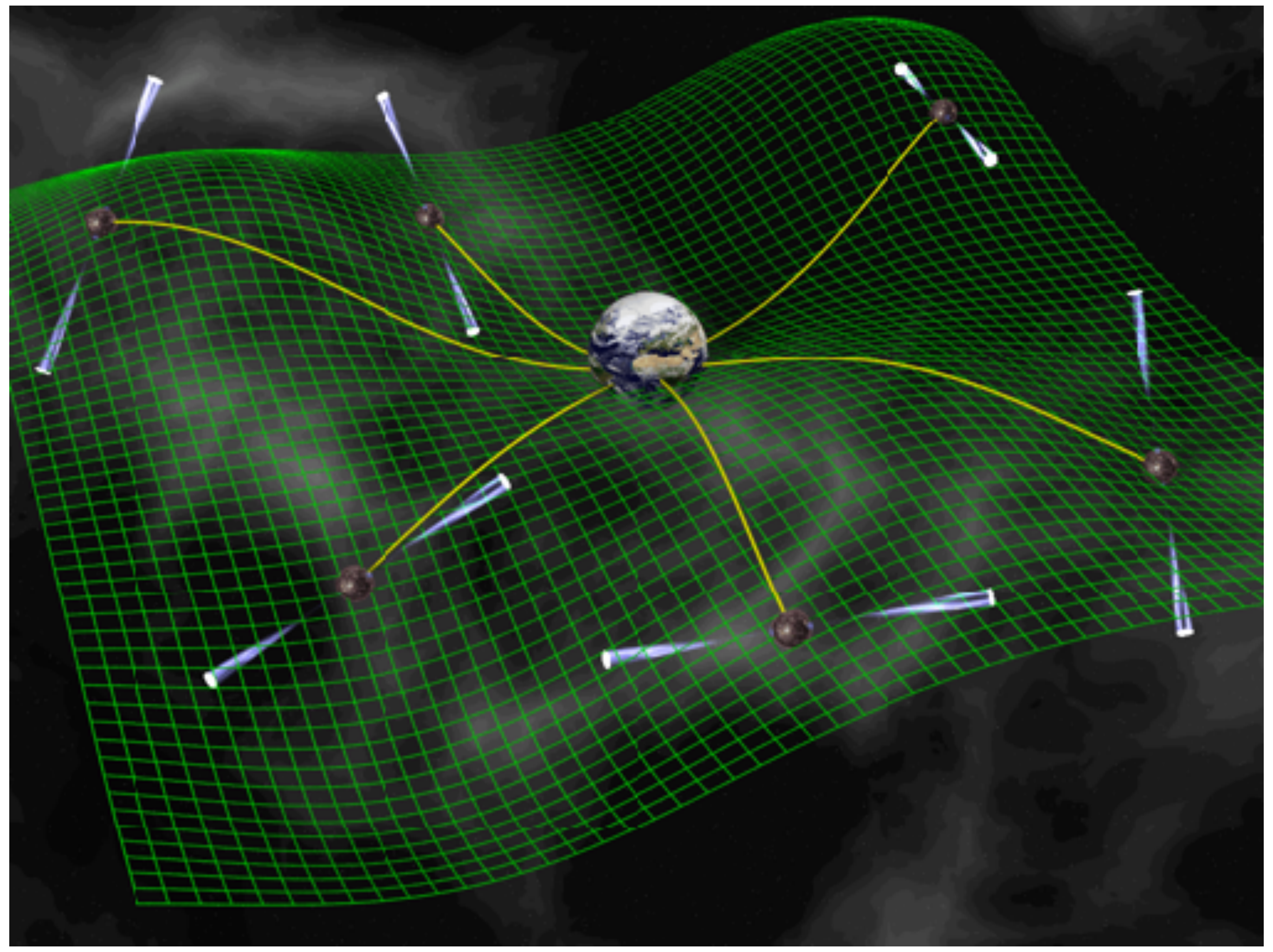


$$\delta x \sim hL \implies \delta x \sim h\lambda_{GW}$$

Drastic Signal Boost - without increasing local noise

PTAs limited by shot noise

Distant Proof Masses



Pulsar Timing Arrays: Detect gravitational waves by looking for modulation in the arrival times of pulsar signals

Works because pulsars are known to be stable clocks

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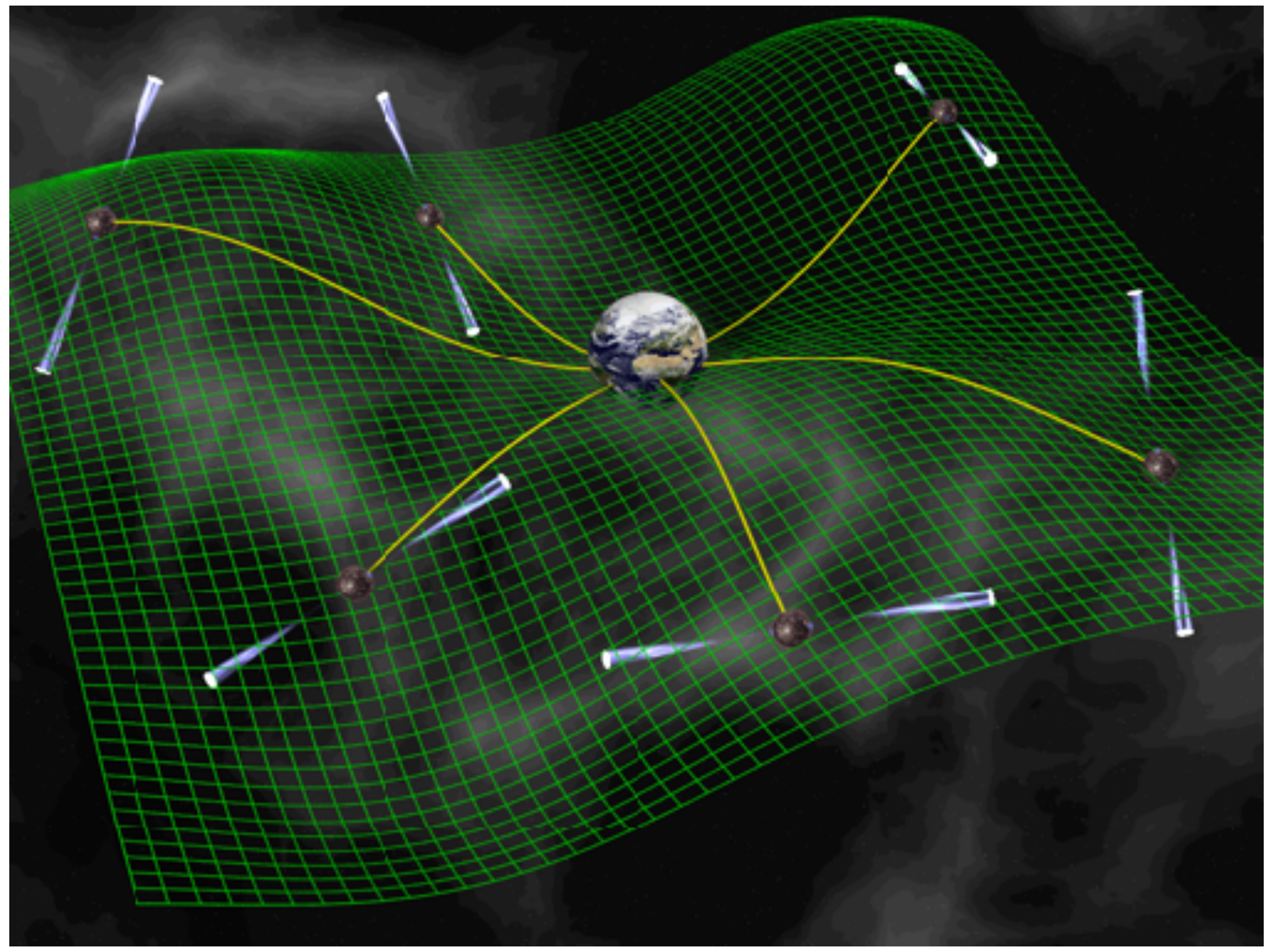

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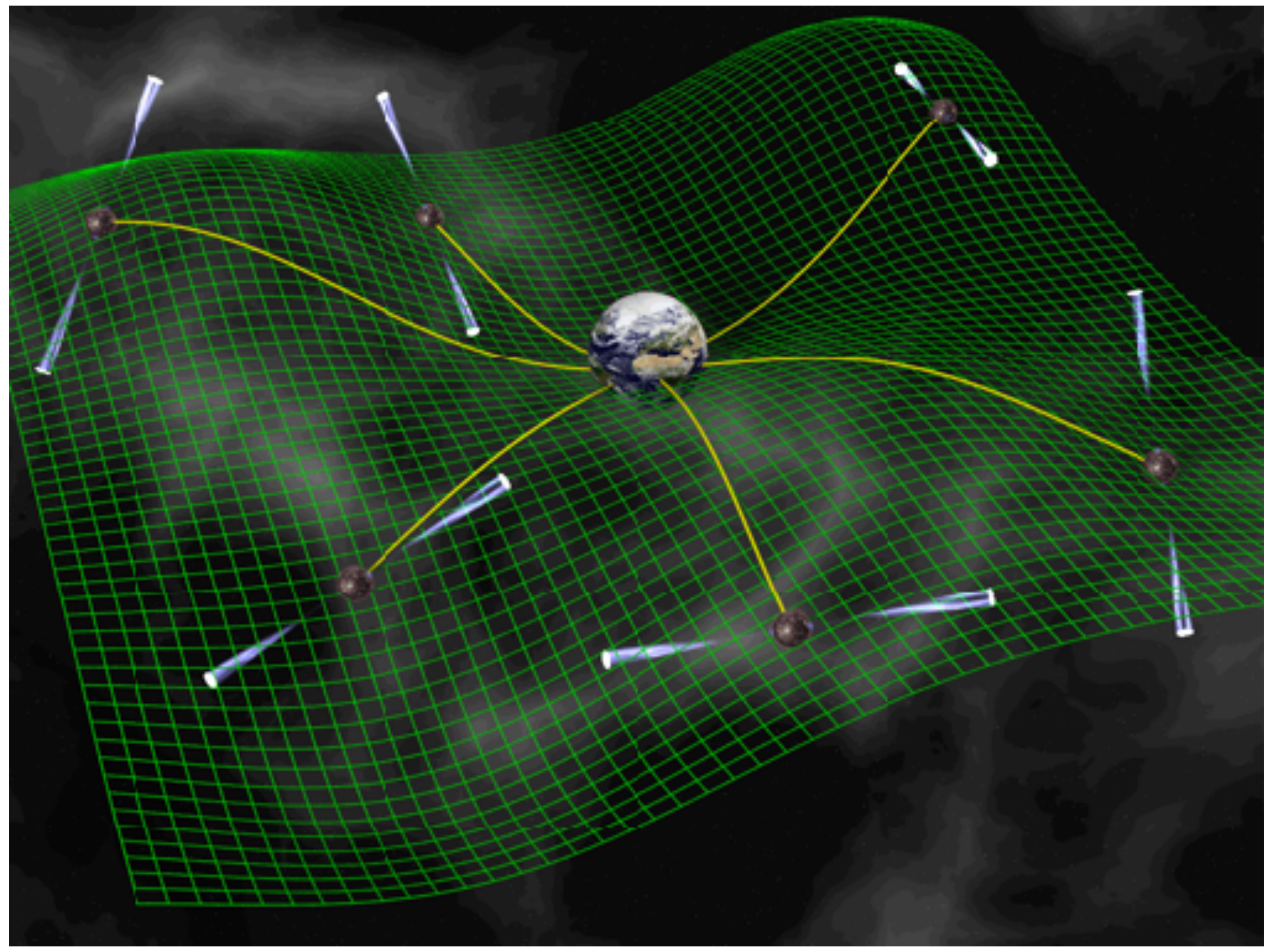

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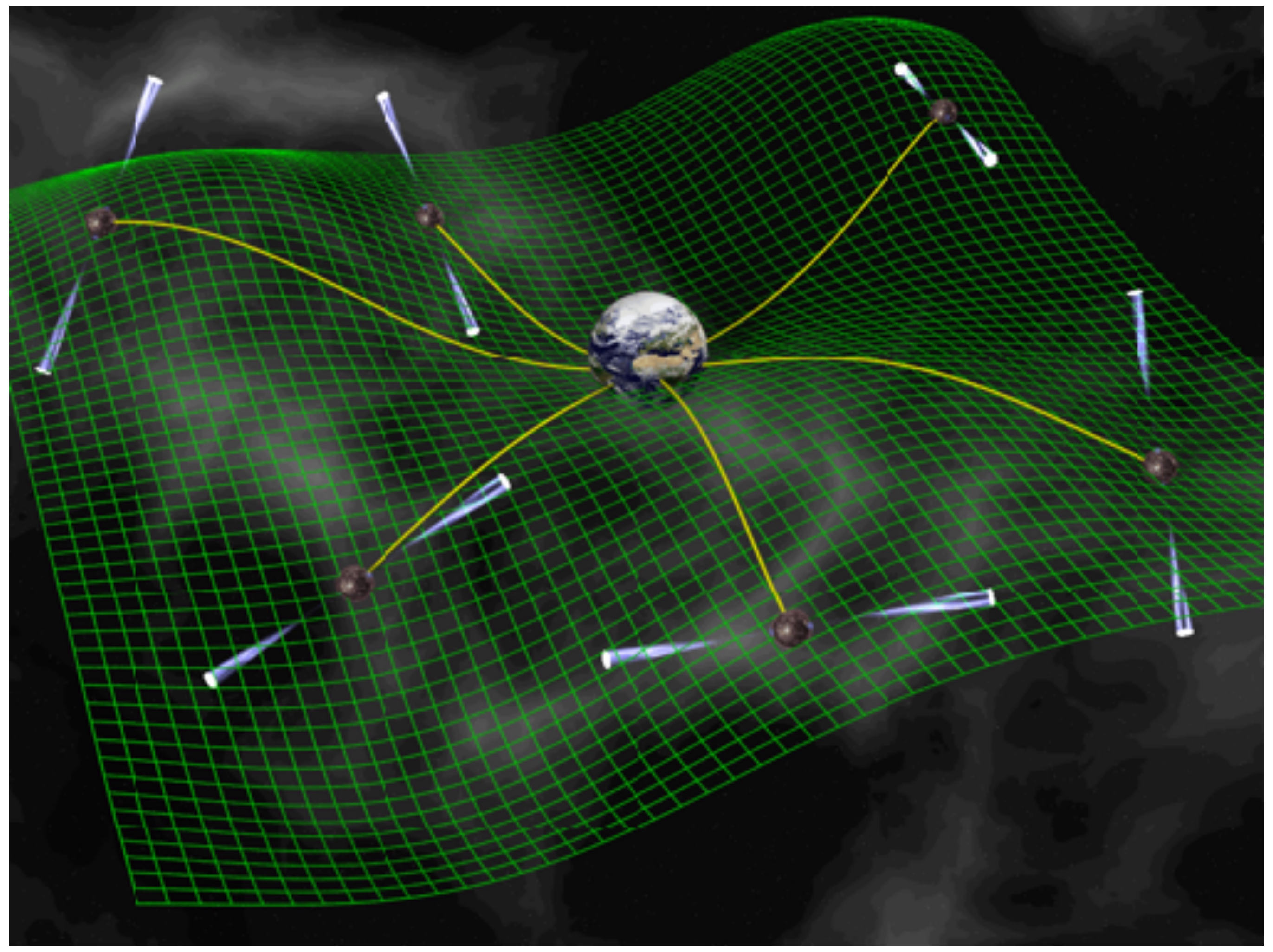

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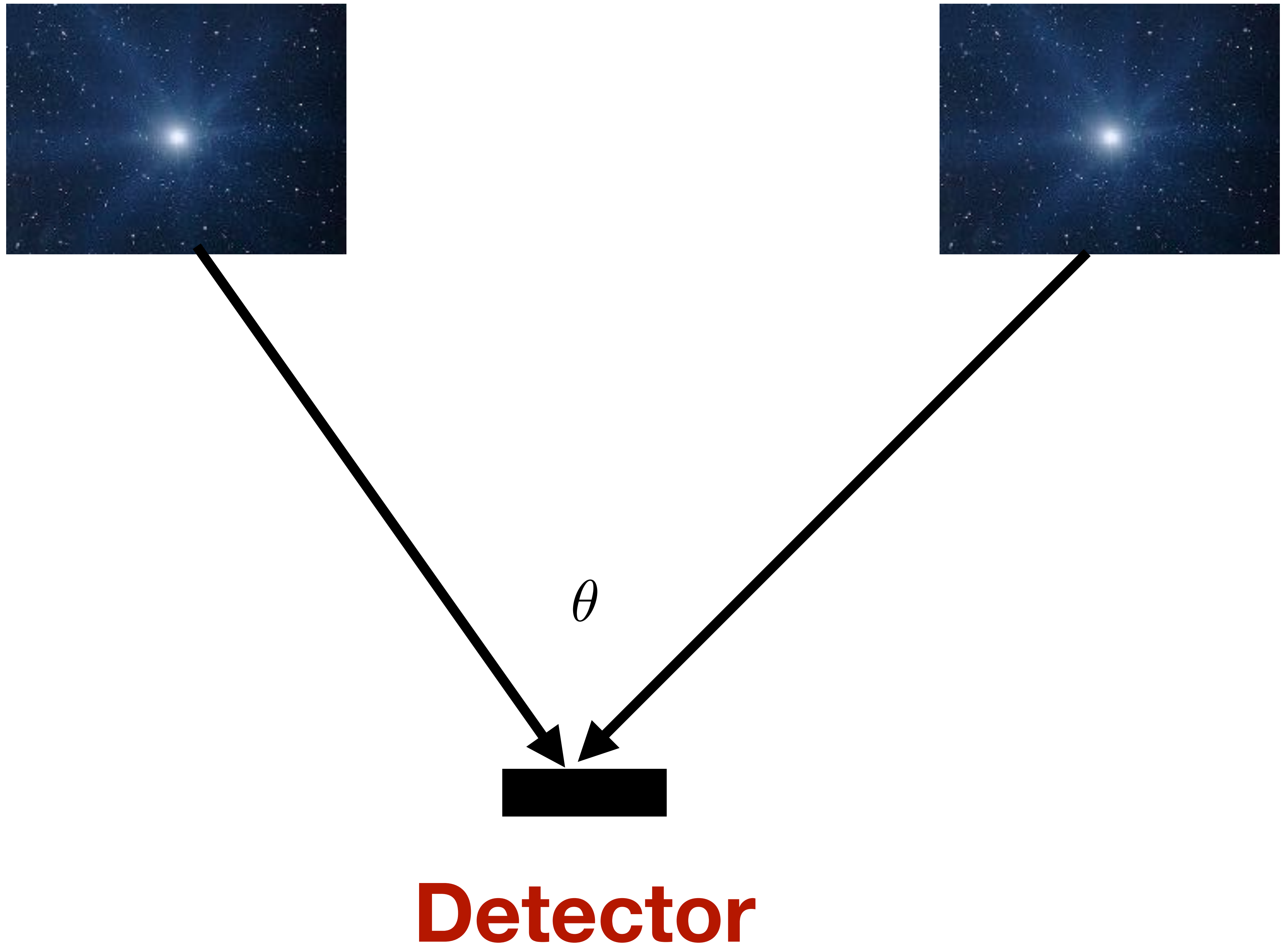
Measure center of mass position via angle measurement?

Astrometry



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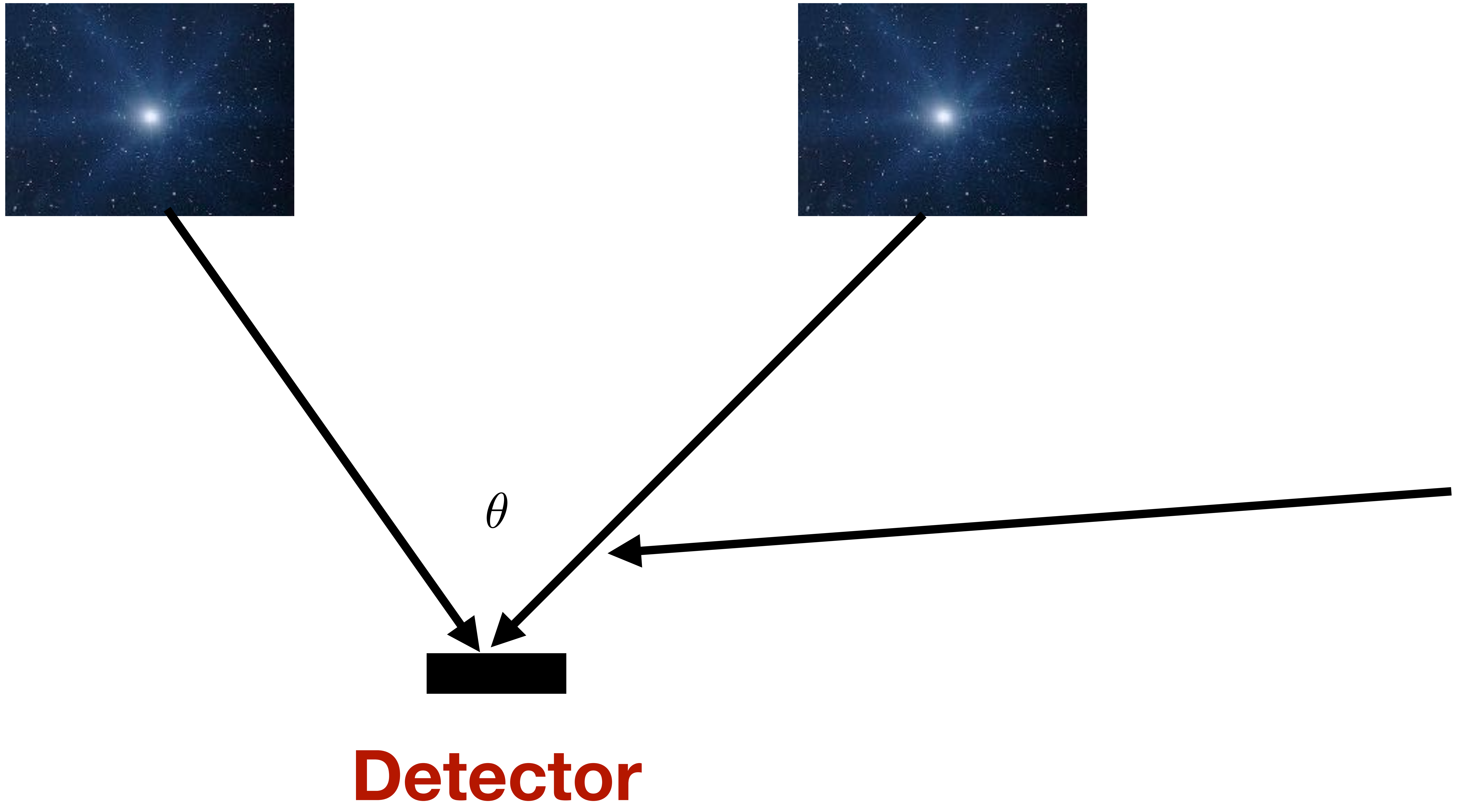

Gravitational wave bends the path taken by light near the detector

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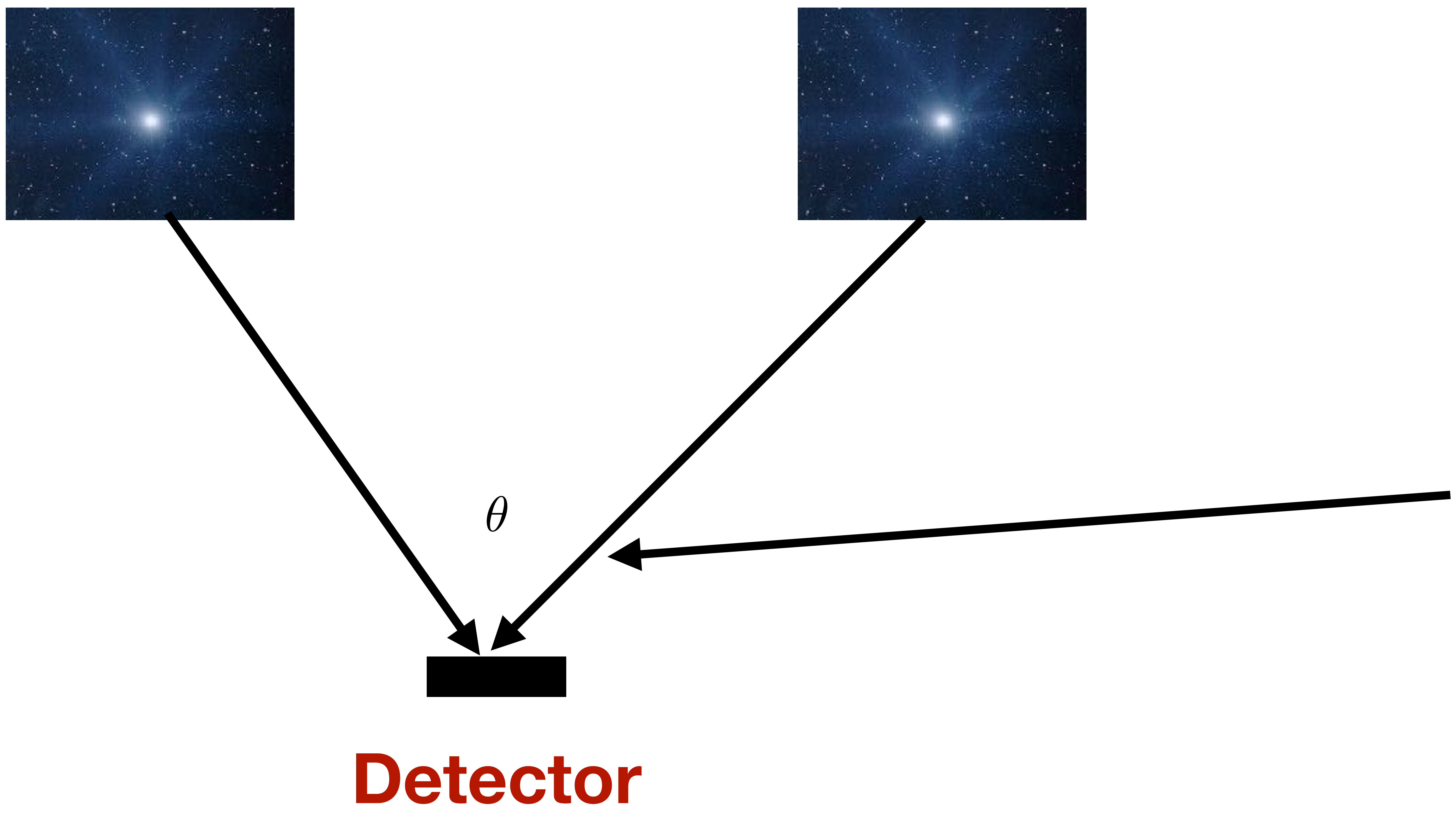

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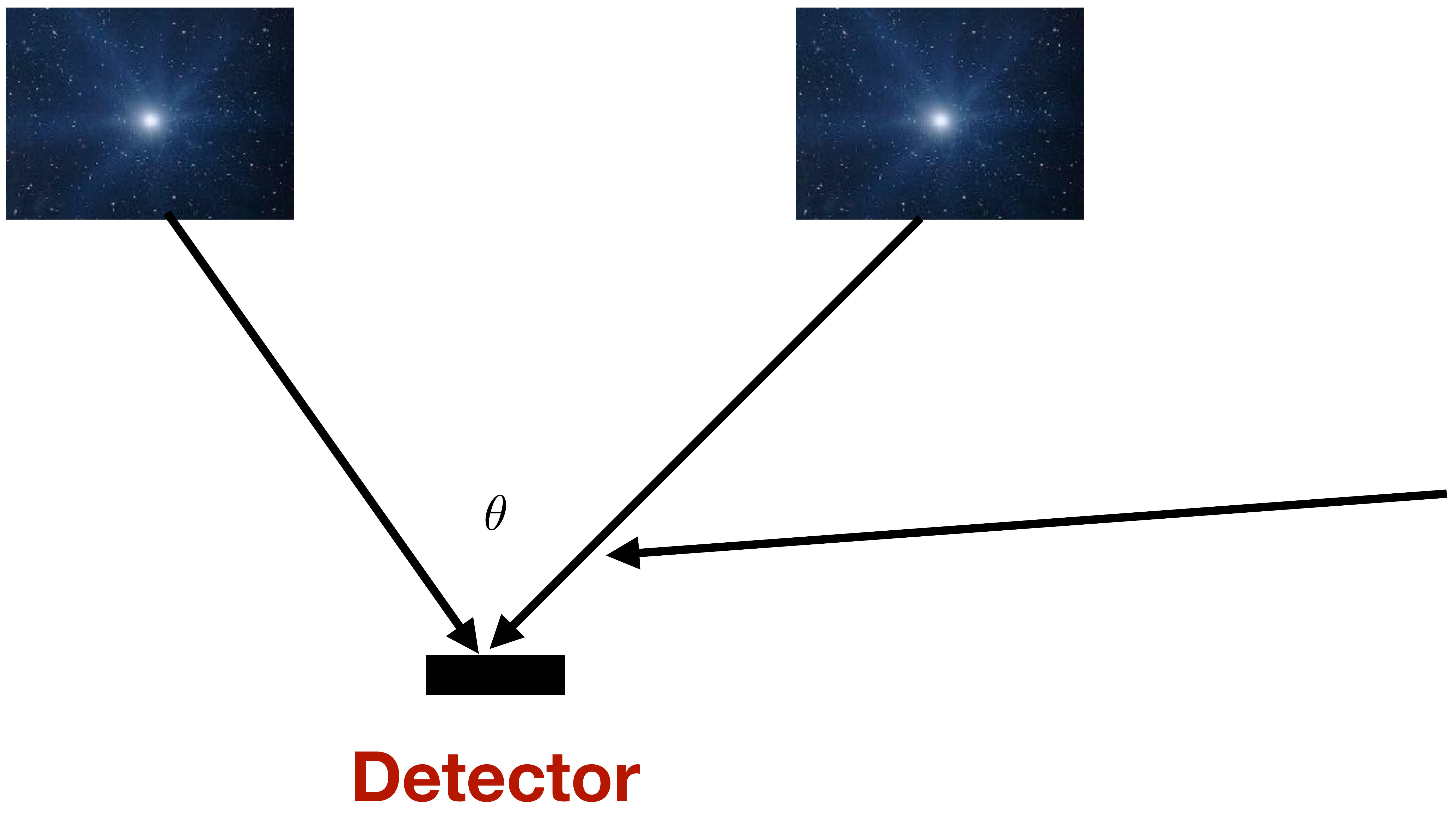

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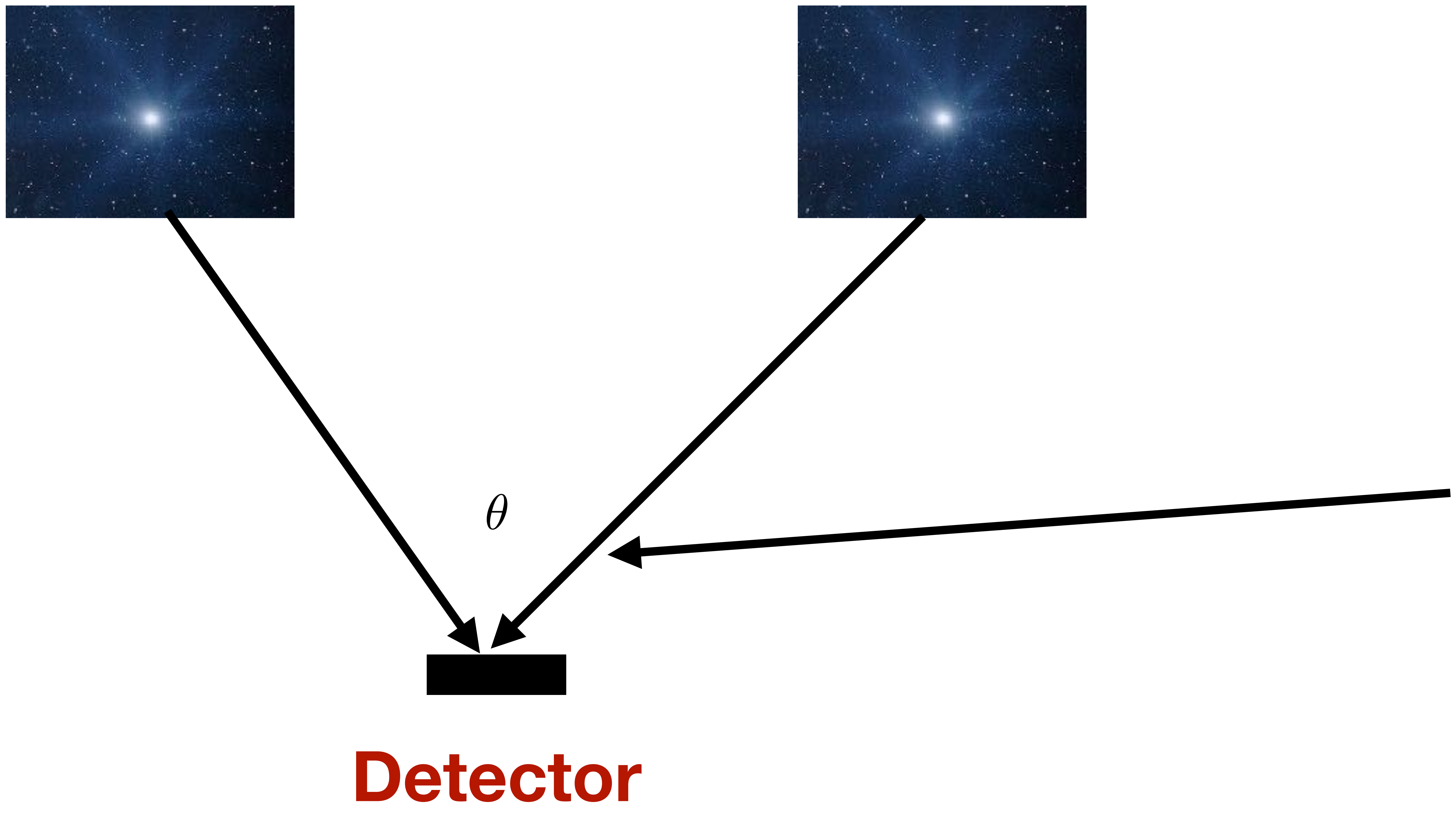

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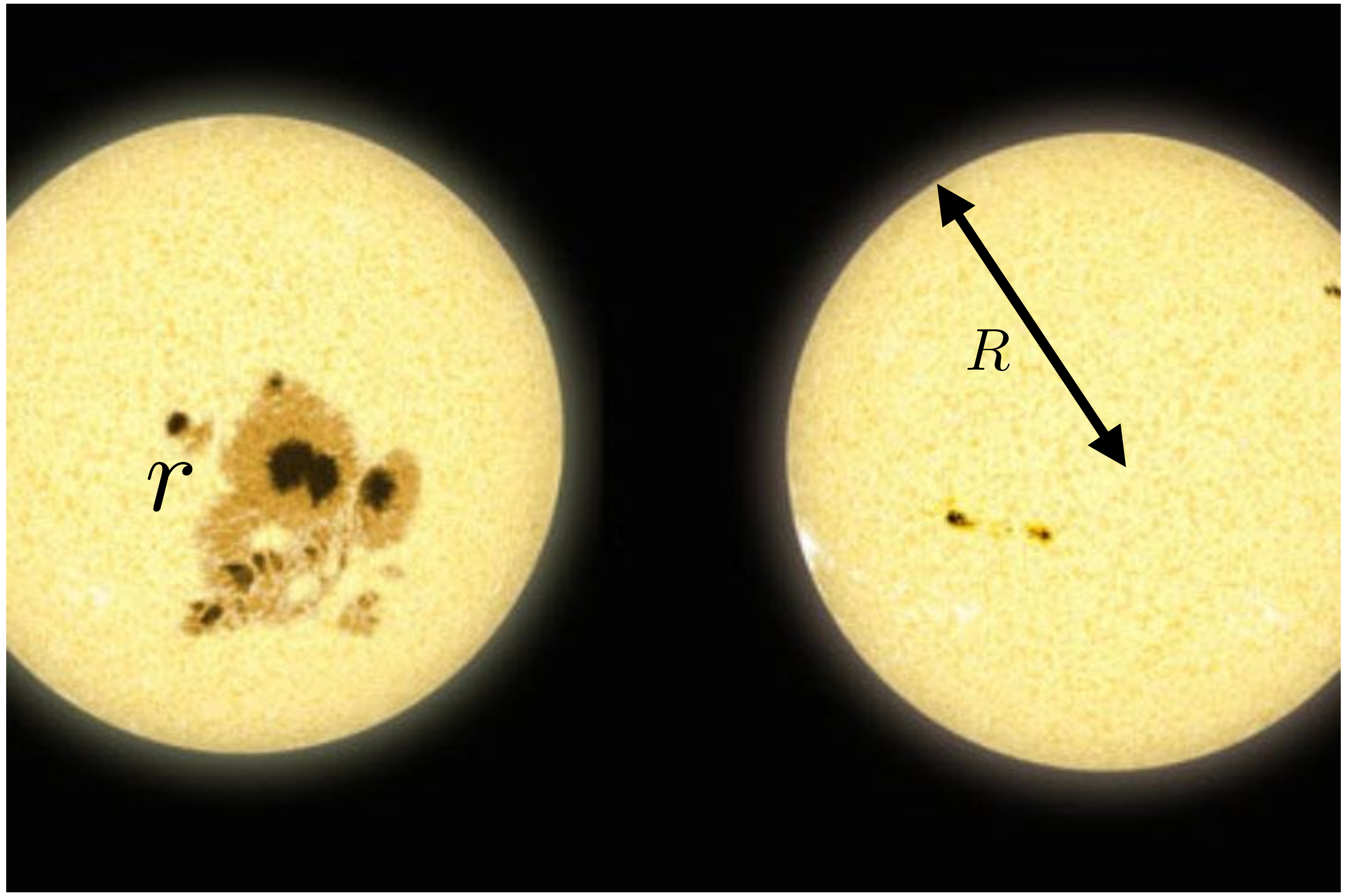
How stable? How do we measure?

Stability

Measuring position via light from object
I.e. photometric center instead of center of mass



Motion of star spot leads to wobble of photometric center

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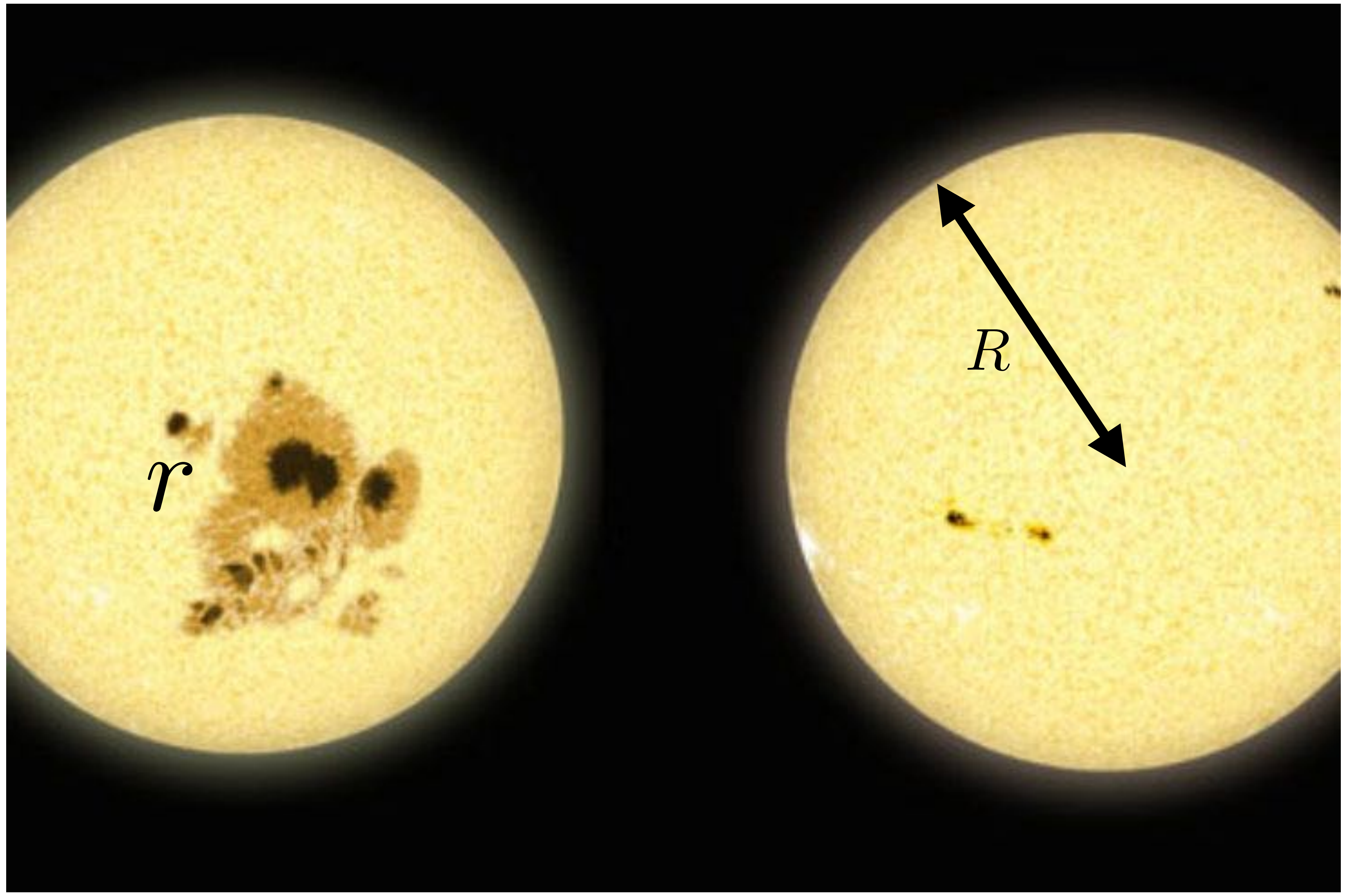

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$$\delta\theta \sim \left(\frac{r}{R}\right)^2 \frac{R}{L}$$

r: spot size

R: stellar radius

L: distance to star

Smaller R => Larger spot size
Longer L => Larger spot size

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White Dwarfs?

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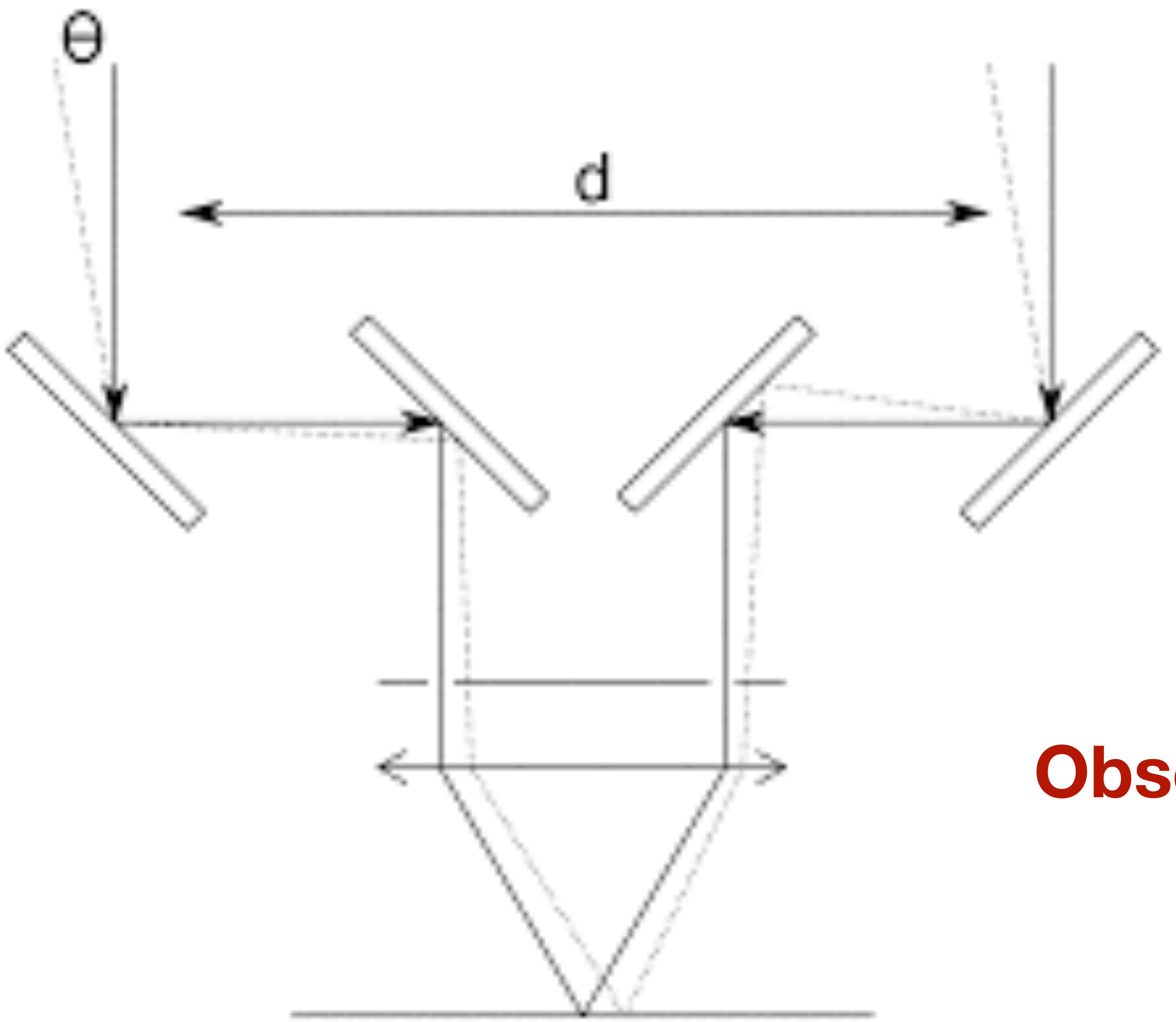
Astrometry of white dwarfs?

Stellar Imager



$$\delta\theta \sim \frac{\lambda}{d} \frac{1}{\sqrt{N_\gamma}}$$

$$\lambda \sim 120 \text{ nm}, d \sim 1 \text{ km} \implies h \sim 10^{-16}$$

(For white dwarf @ kpc)

Observe small number of stars for long periods

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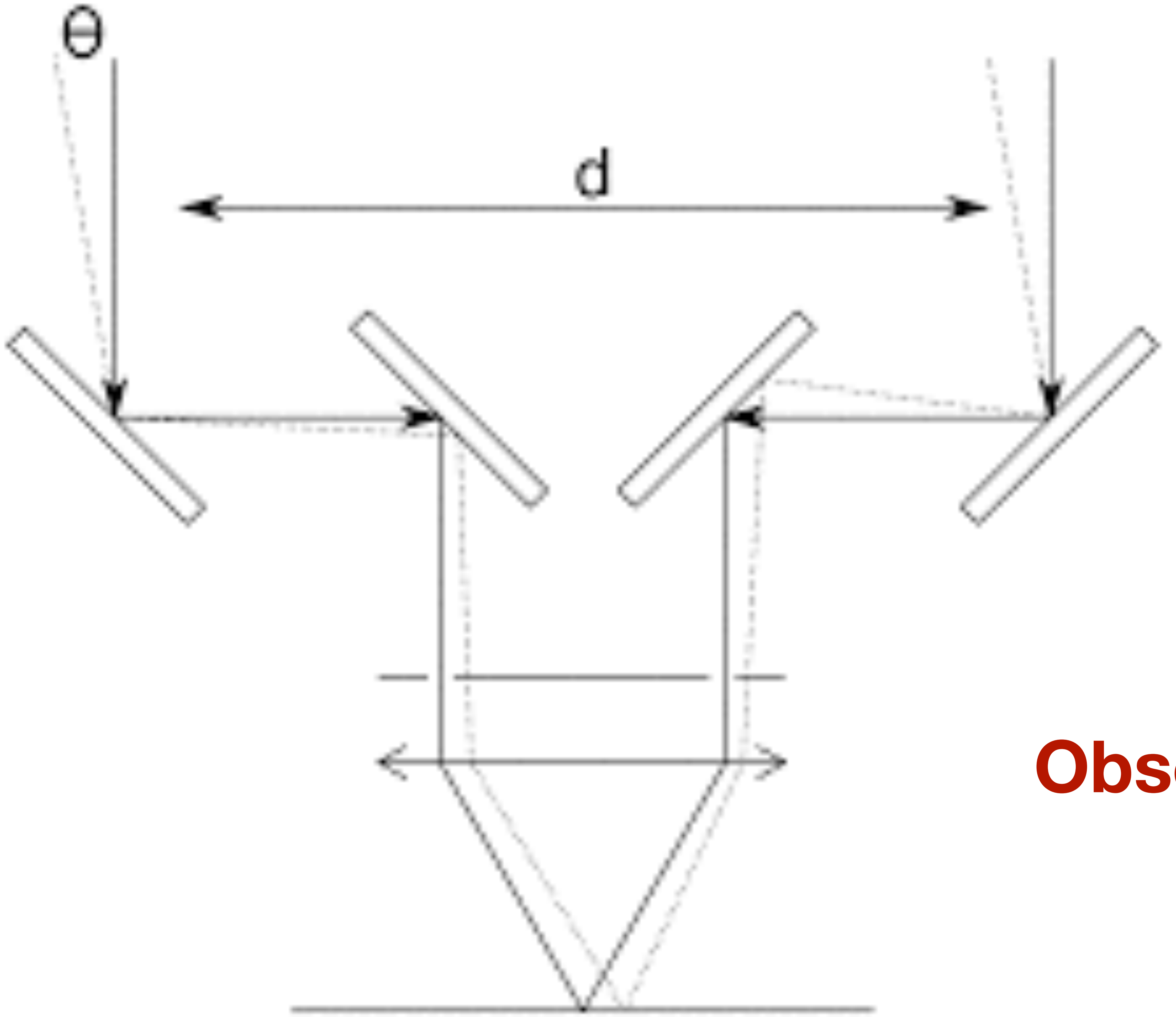

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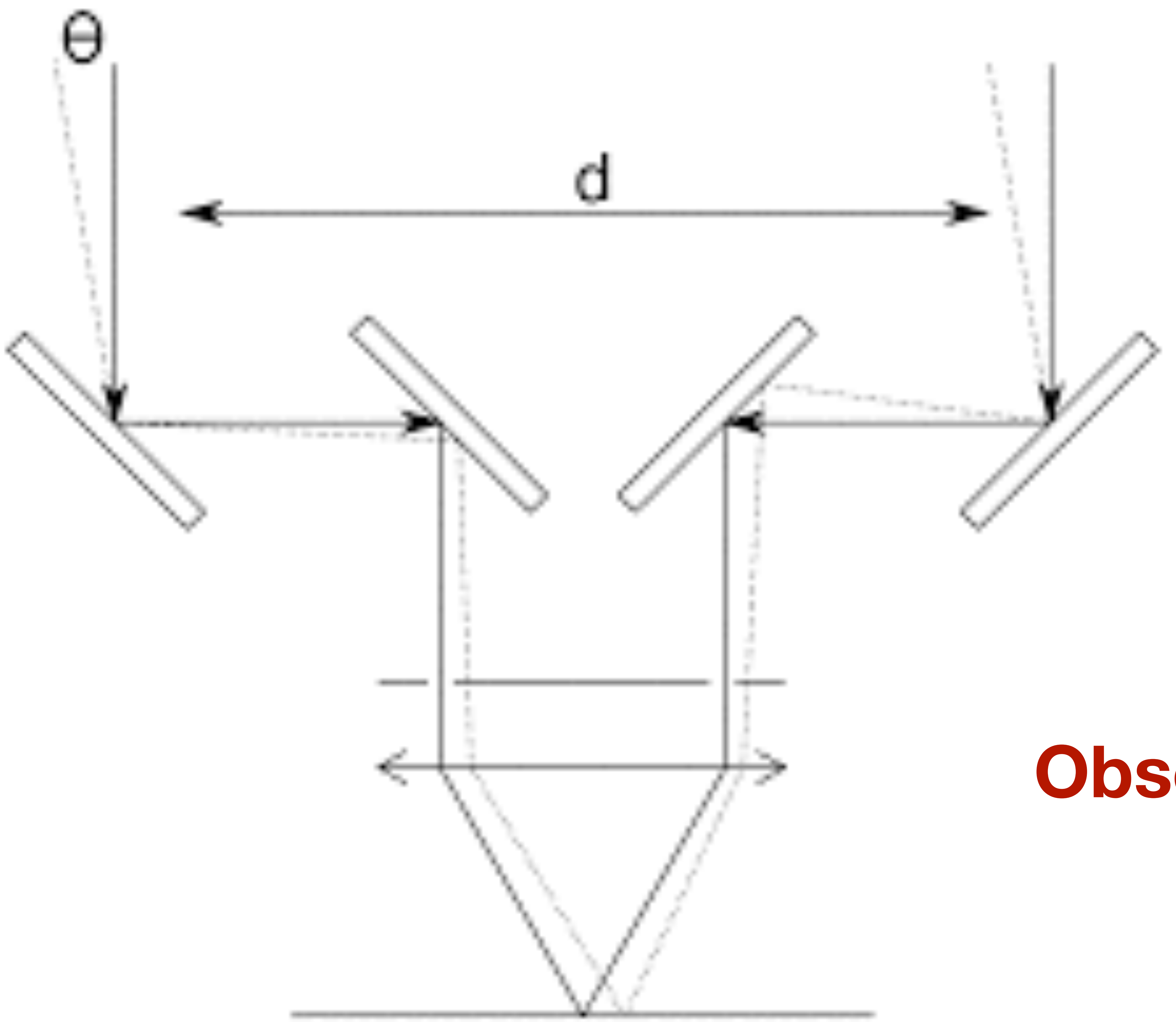

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Adds to Science Case of such missions!

Conclusions

The Gravitational Wave Spectrum

Gravitational wave astronomy is here to stay!

Strong science case to probe entire gravitational wave spectrum

Strong case for using asteroids as test masses in the μHz frequency range. Motivates asteroid seismology measurements and development of space-qualified atomic clocks

Gravity gradient noise from asteroids below μHz motivates astrometry of photometrically stable non-magnetic white dwarfs. Adds to the science case of interferometry missions like Stellar Imager