Astrometric GW Detection via Stellar Interferometry

PPC 2022

Washington University in St. Louis
St Louis, MO, USA

June 8, 2022

M.A.F., P. W. Graham, B. Macintosh, S. Rajendran [2204.07677].

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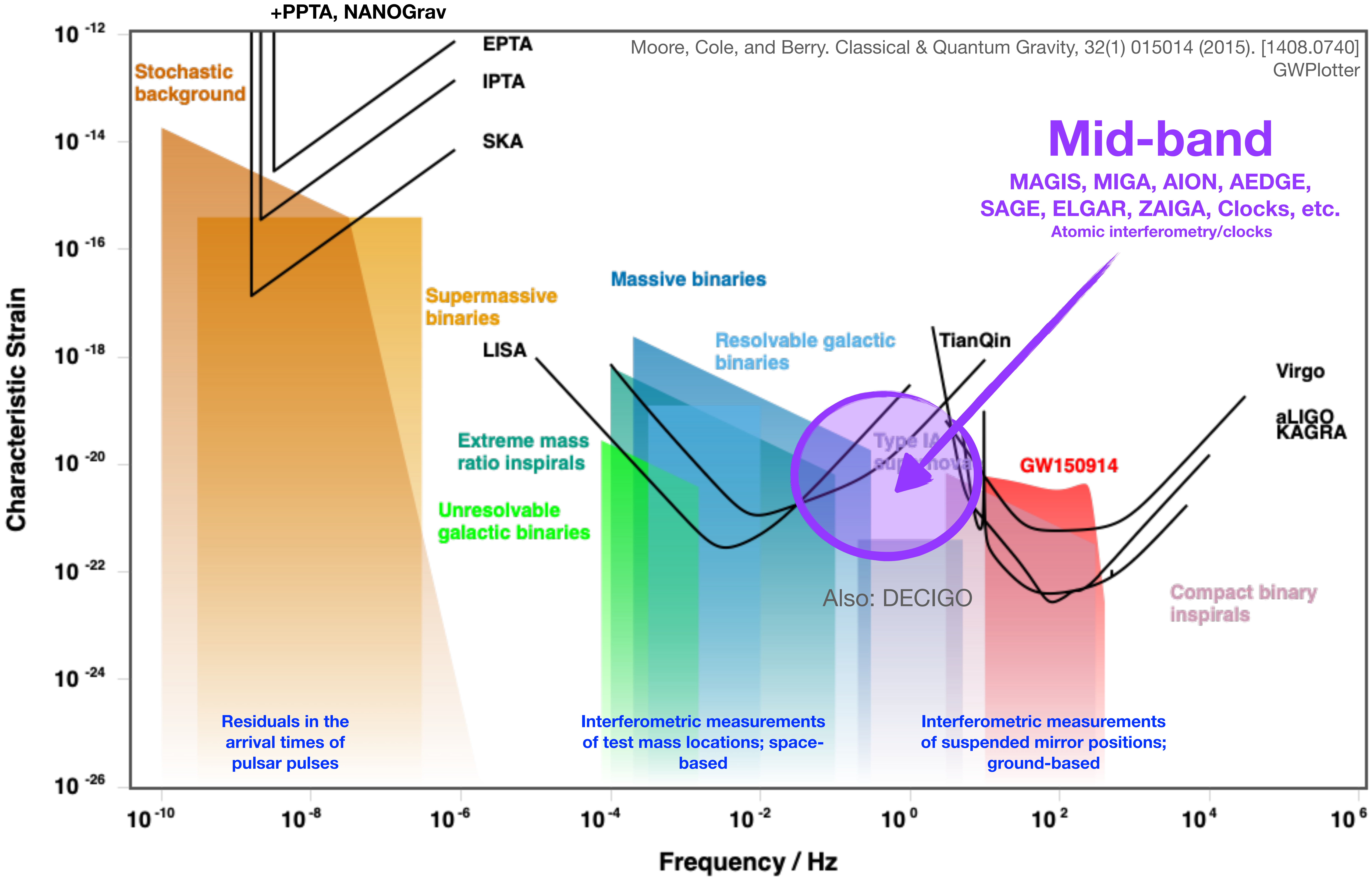
JOHNS HOPKINS UNIVERSITY

GW Detection Landscape



+PPTA, NANOGrav

Moore, Cole, and Berry. Classical & Quantum Gravity, 32(1) 015014 (2015). [1408.0740]
GWPlotter

Mid-band

MAGIS, MIGA, AION, AEDGE, SAGE, ELGAR, ZAIGA, Clocks, etc.

Atomic interferometry/clocks

Also: DECIGO

Strong science case for broad coverage!

Existing / proposed facilities provide good coverage.

But there is a gap

…in coverage

…**not** sources!

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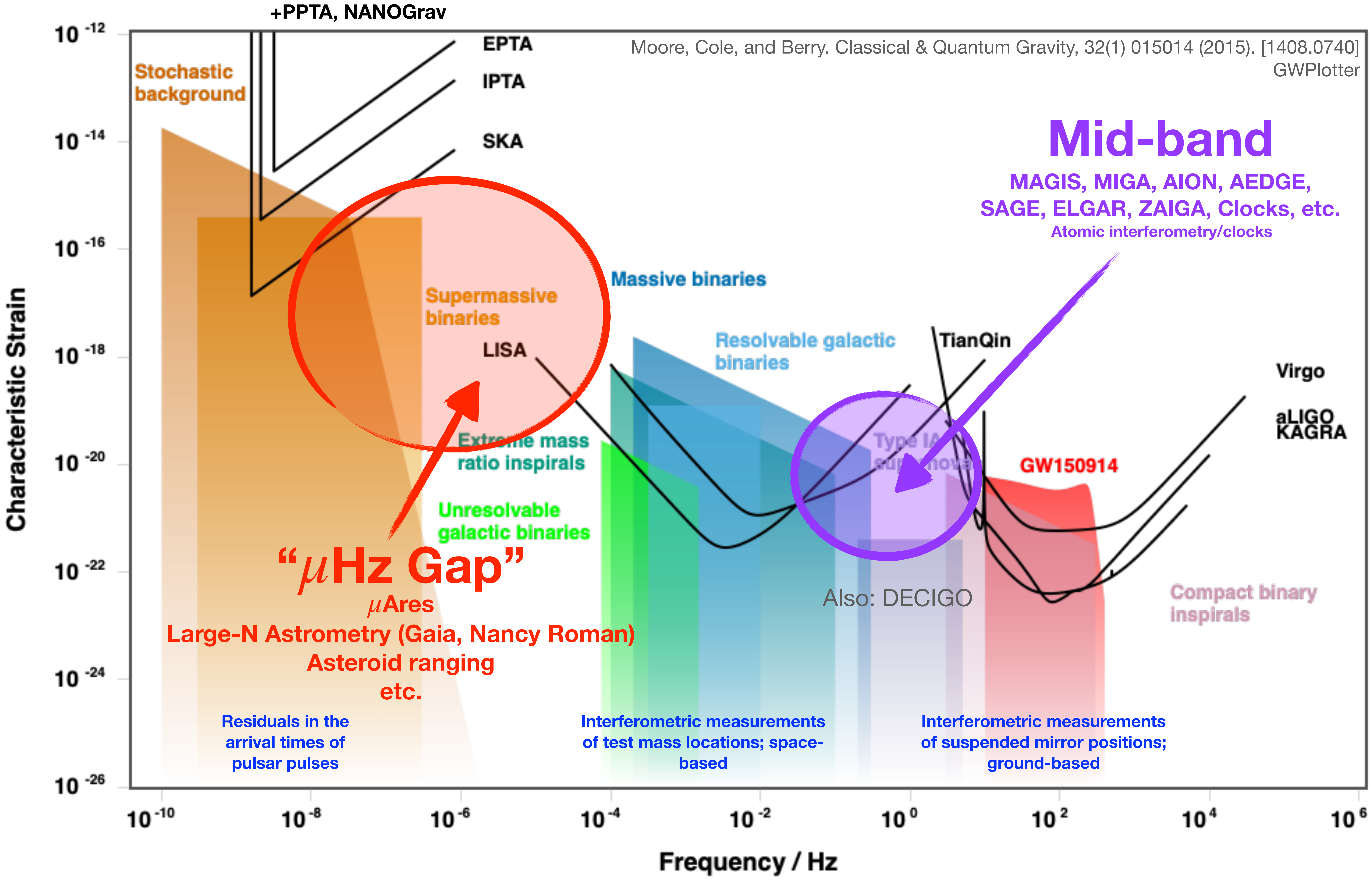

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“μHz Gap”

μAres
Large-N Astrometry (Gaia, Nancy Roman)
Asteroid ranging
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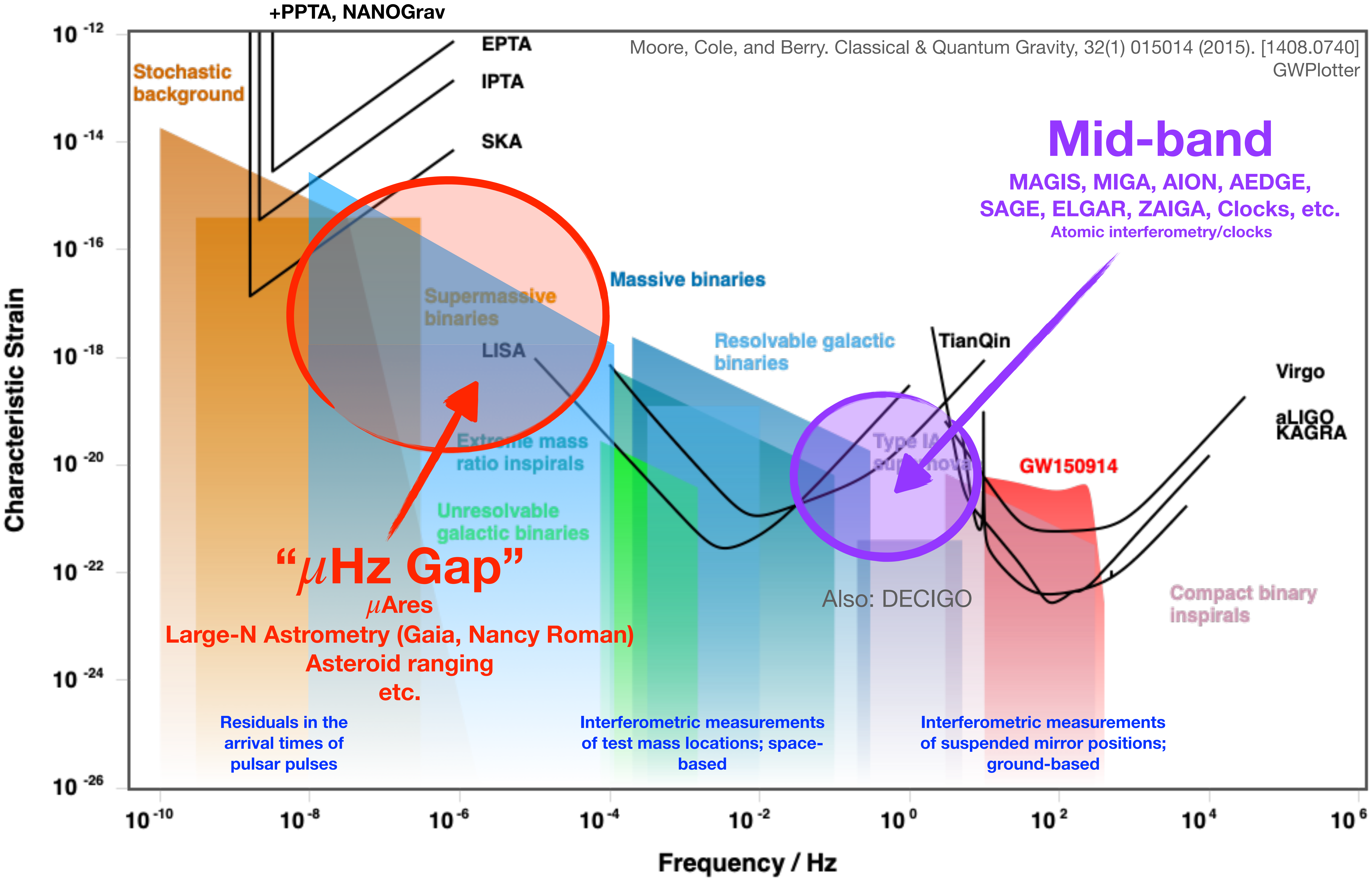

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The “μHz Gap”

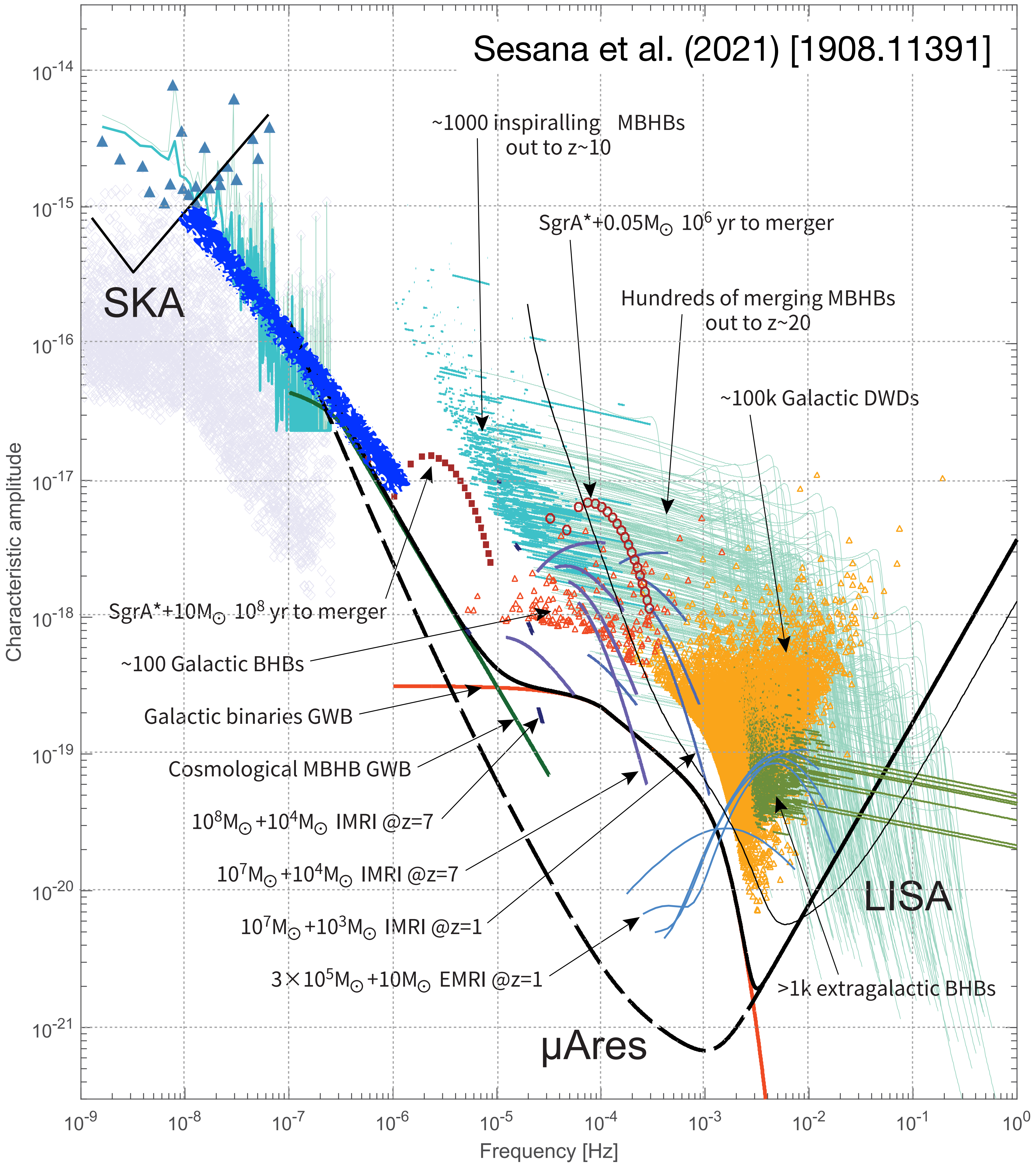
Interesting sources:

- Galactic black hole binaries (BHBs)
- Cosmologically distant massive binary black holes (MBHBs)
- $10M_\odot$ spiraling into SgrA*
- Intermediate mass-ratio inspires (IMRIs)
- … and other non-GW new physics

Existing observational studies and approaches:

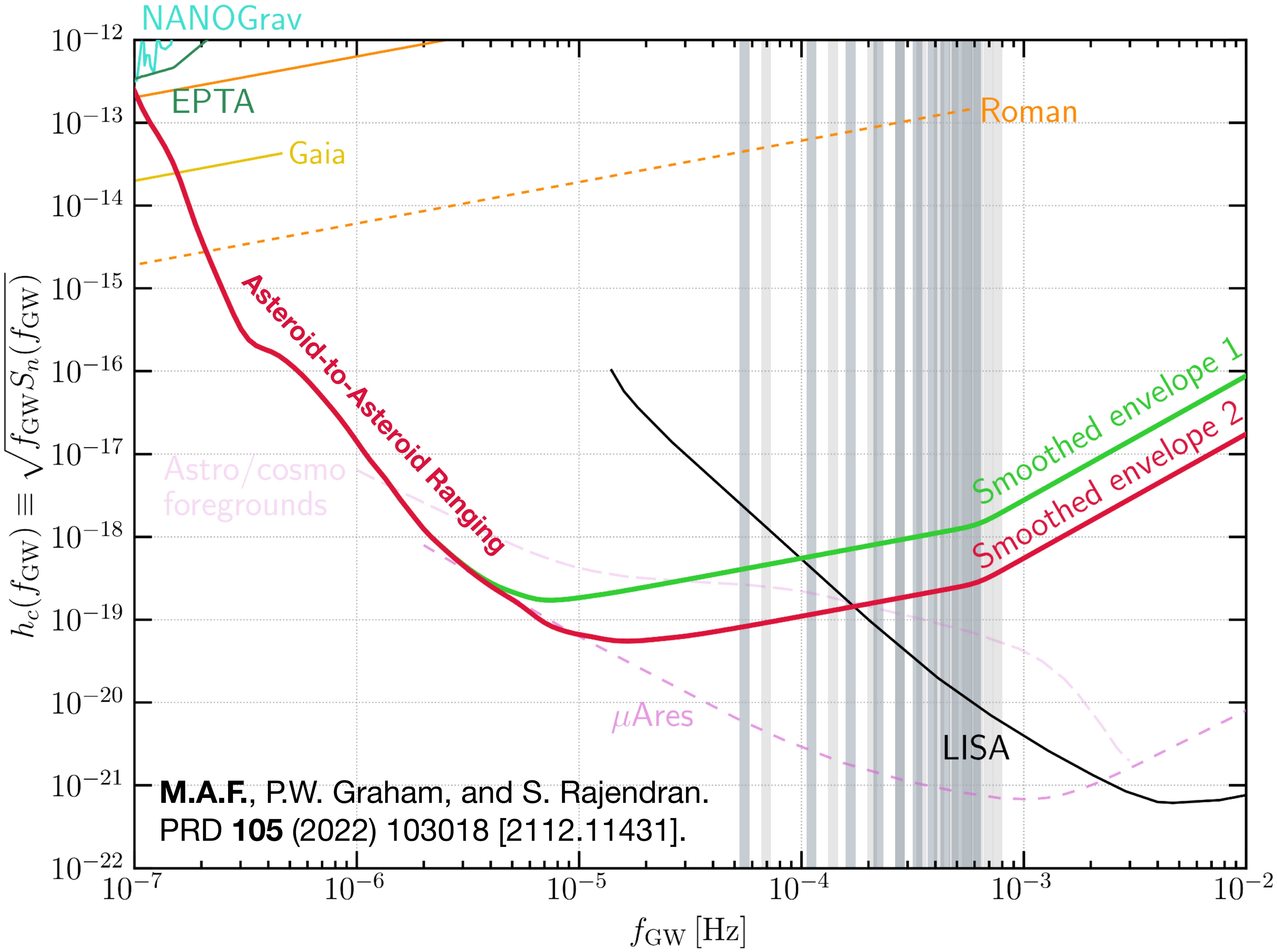
- Large-N Astrometric Techniques
  Pyne, et al (1996); Schutz (2009); Book and Flanagan (2011); Klioner (2018); Moore, et al (2017); Wang, et al (2021)
- μAres (“LISA-style”: bigger, and better TM)
  Sesana et al. Exp. Astron **51** (2021) 1333
- Asteroid-to-Asteroid Ranging
  M.A.F., P.W. Graham, and S. Rajendran. PRD **105**, 103018 (2022) [arXiv: 2112.11431]
- Binary Orbital Perturbations
  Blas and Jenkins PRL **128** (2022) 101103 & PRD **105** (2022) 064201

The μAres detection landscape



Sesana et al. (2021) [1908.11391]

Existing approaches in this band



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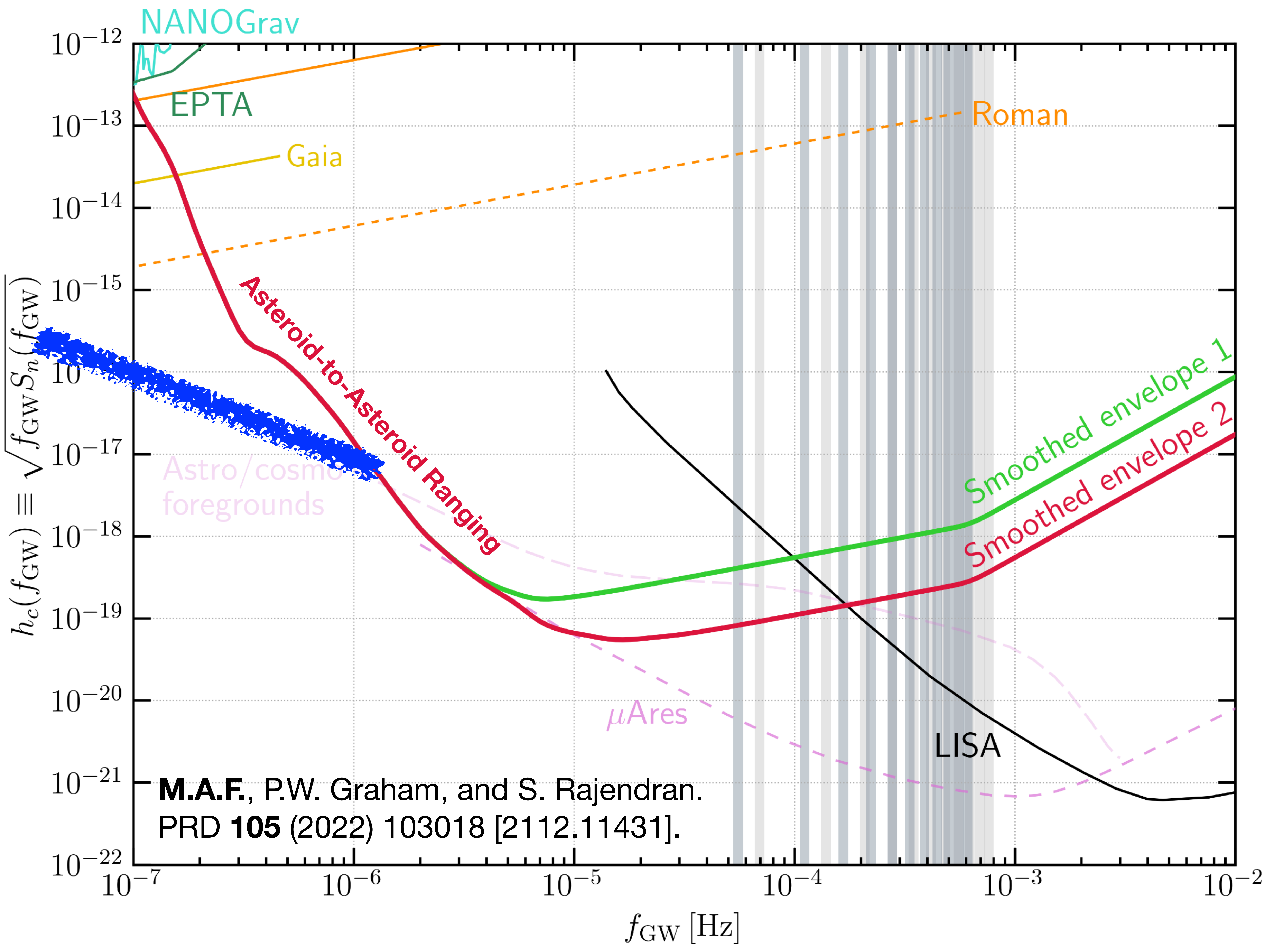

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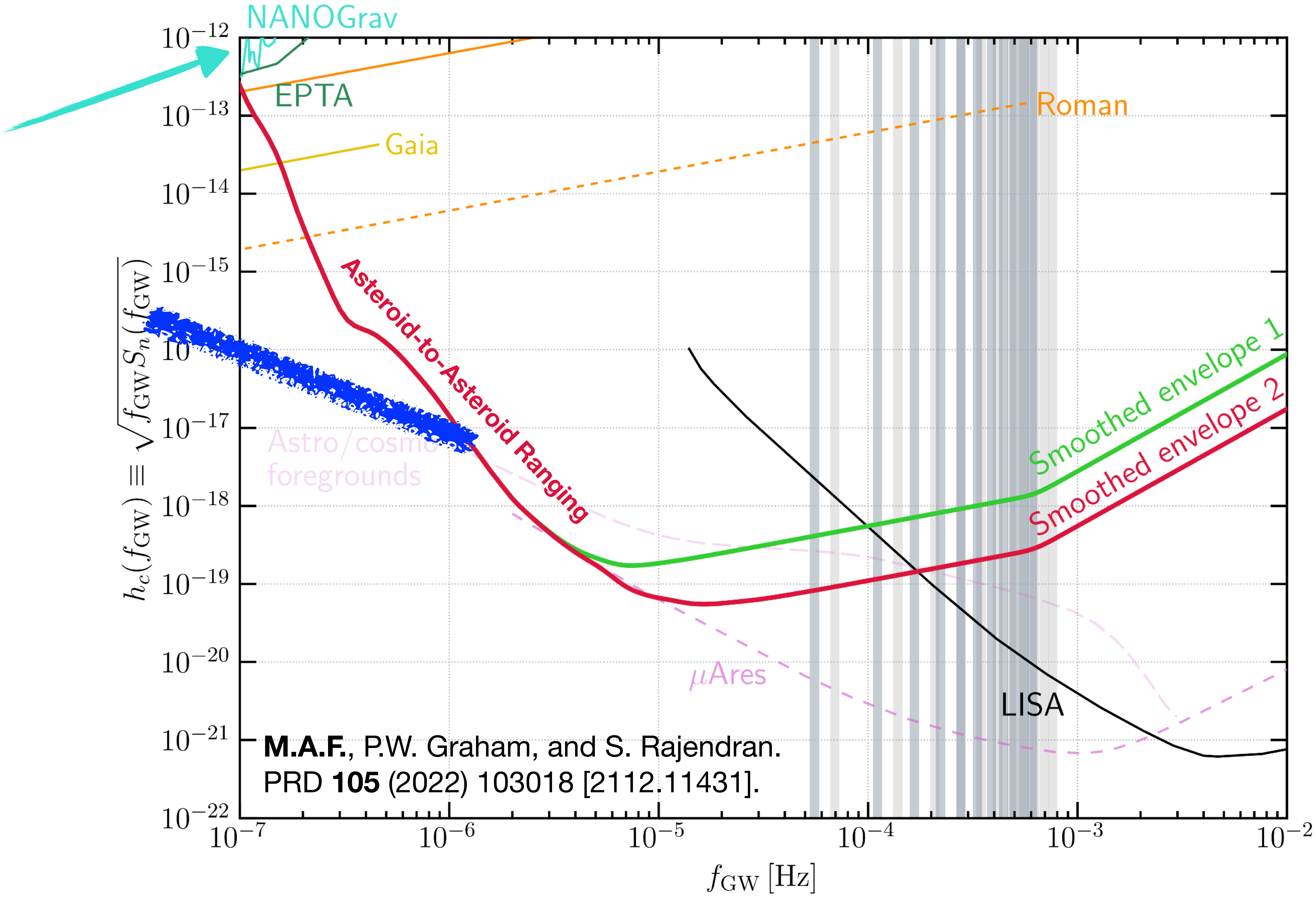

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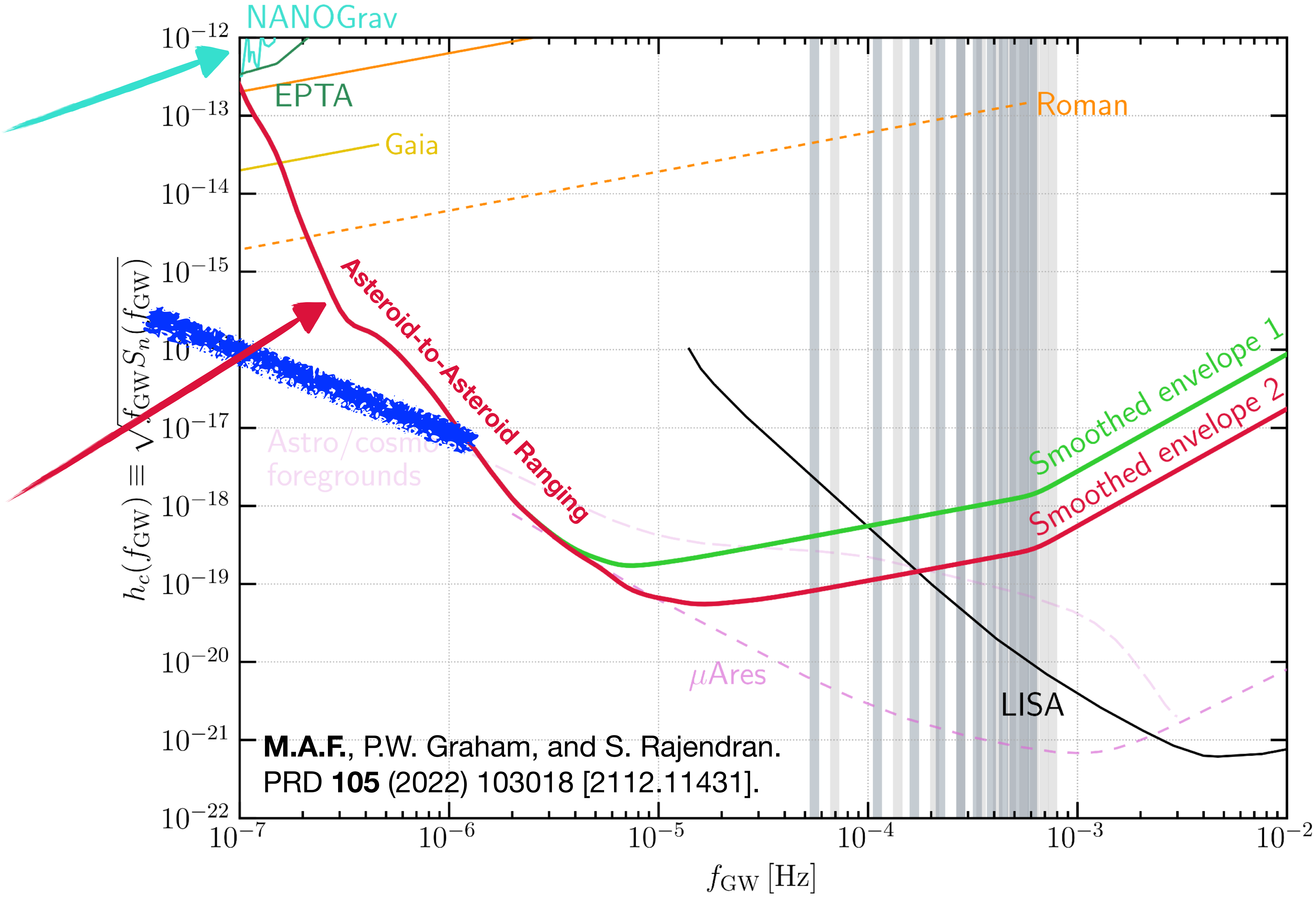

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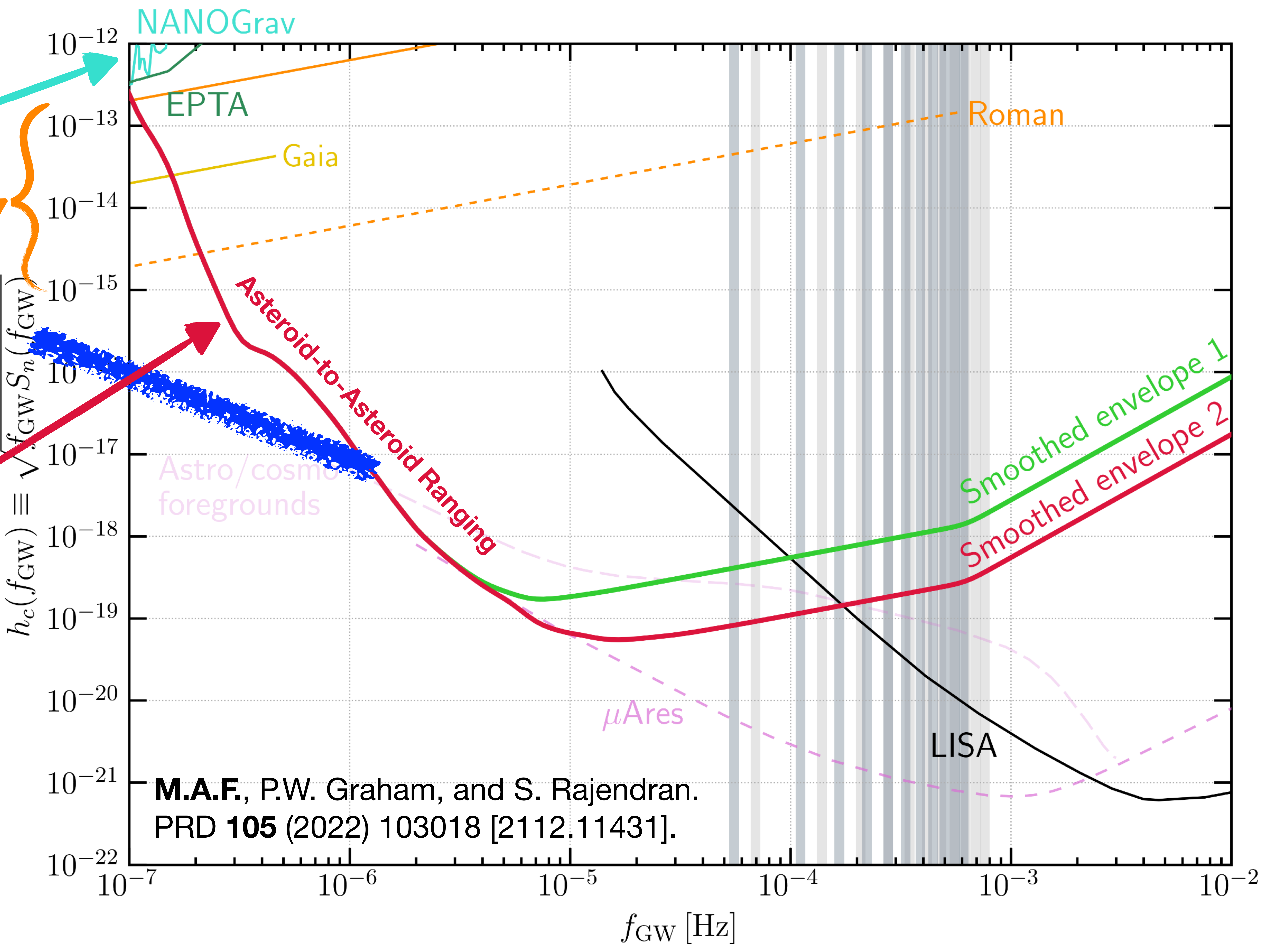

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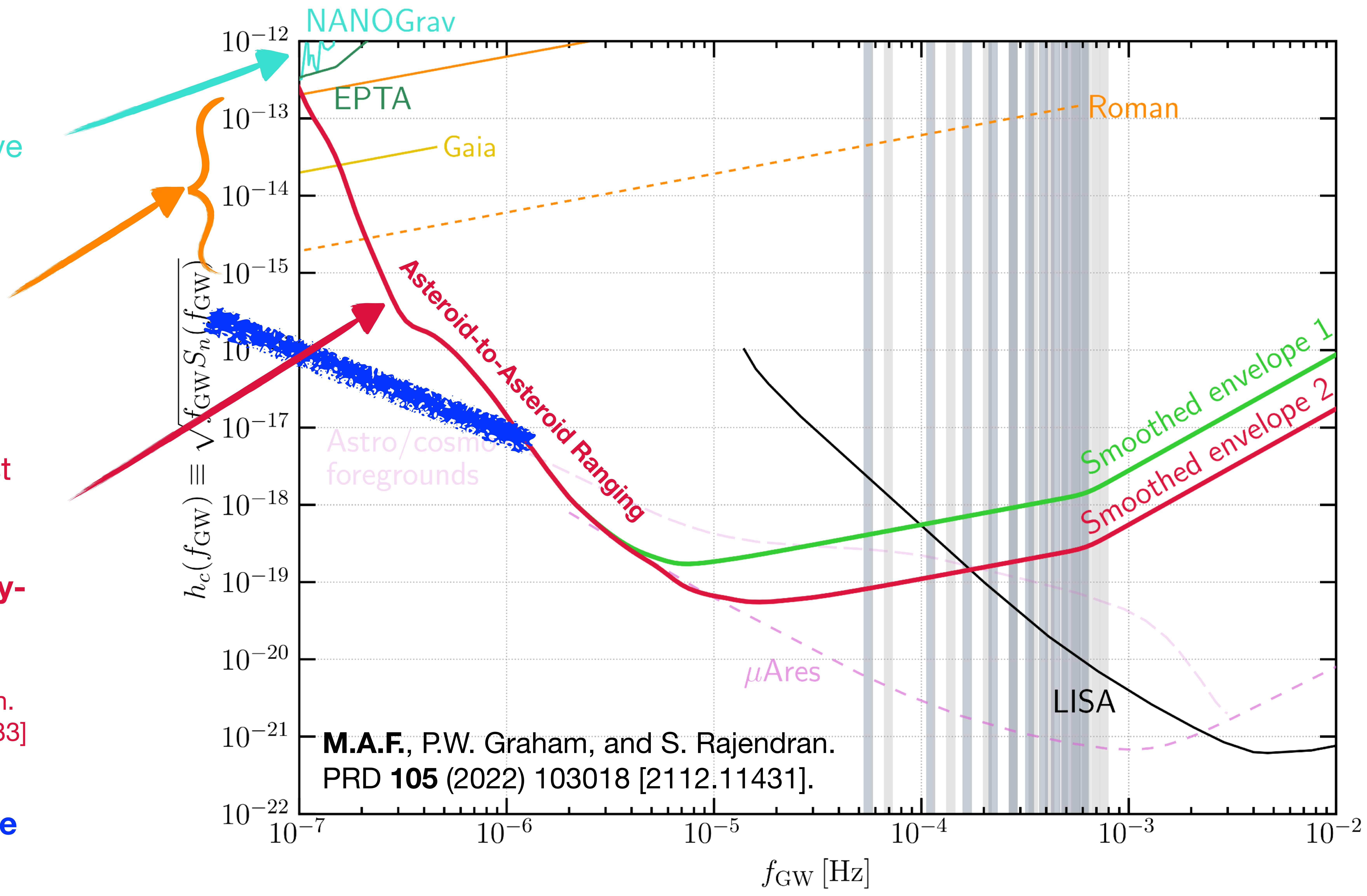
So how can we reach the required sensitivity?



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Astrometric GW detection

A GW passing the detector causes a correlated angular deflection of apparent stellar positions:

See, e.g., Book and Flanagan. PRD **83** (2011) 024024 [arXiv:1009.4192]

$$\delta\theta \sim -\frac{h_{+}^{(0)}}{2}\sin(\theta)\cos(2\phi)\cos(\omega_{\rm GW}t) - \frac{h_{\times}^{(0)}}{2}\sin(\theta)\sin(2\phi)\cos(\omega_{\rm GW}t+\alpha);$$

$$(d_{\rm source}\omega_{\rm GW} \gg 1)$$

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The effect is $\mathcal{O}(h_{+,\times}^{(0)})$! **Extremely small** for single stars.

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Standard approach

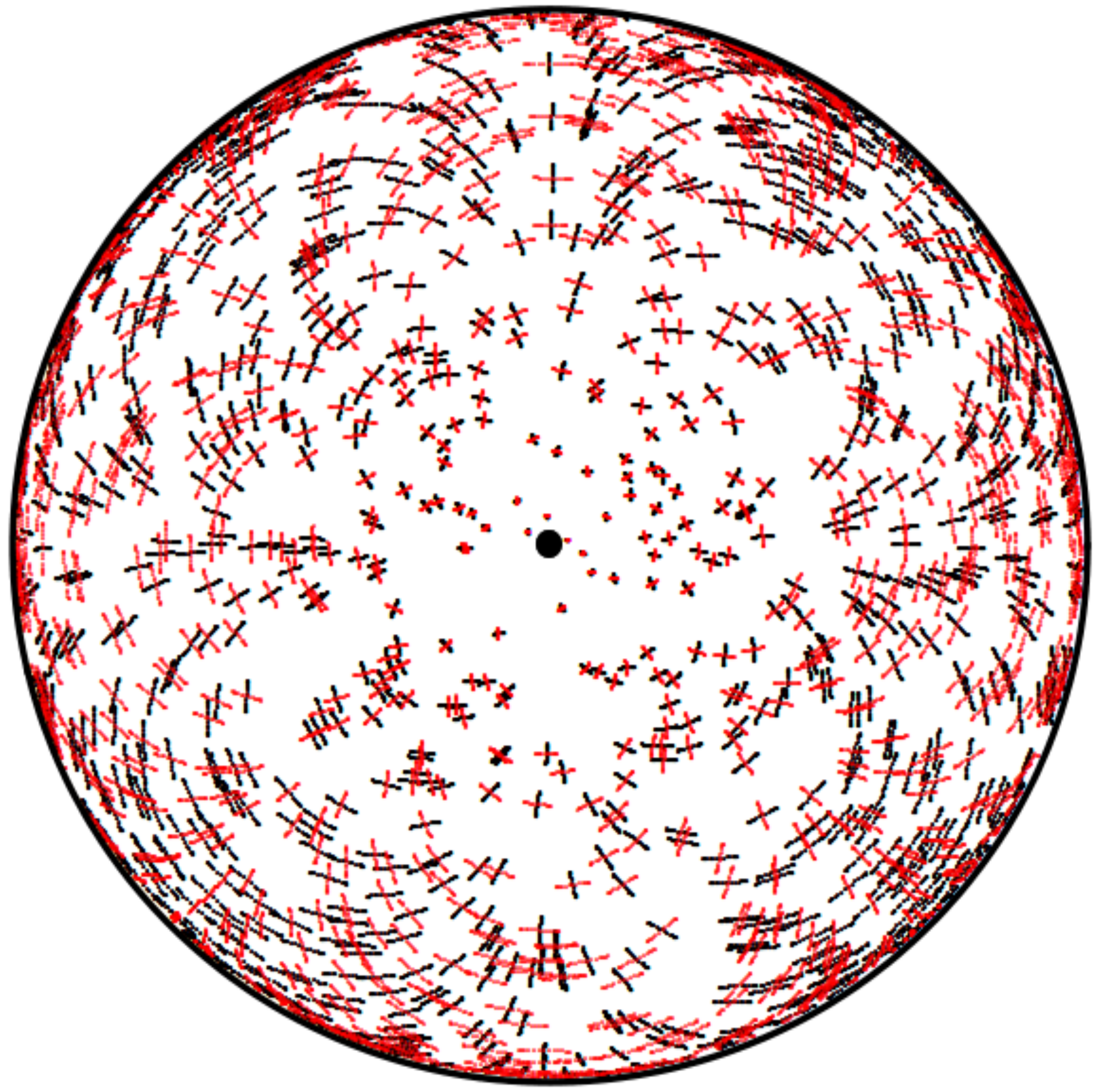
Extremely large-N surveys (Gaia, Roman Space Telescope)

Single-star astrometric precision $\sigma_\theta^{(1)} \gg h_c$

Exploit large-N statistics:

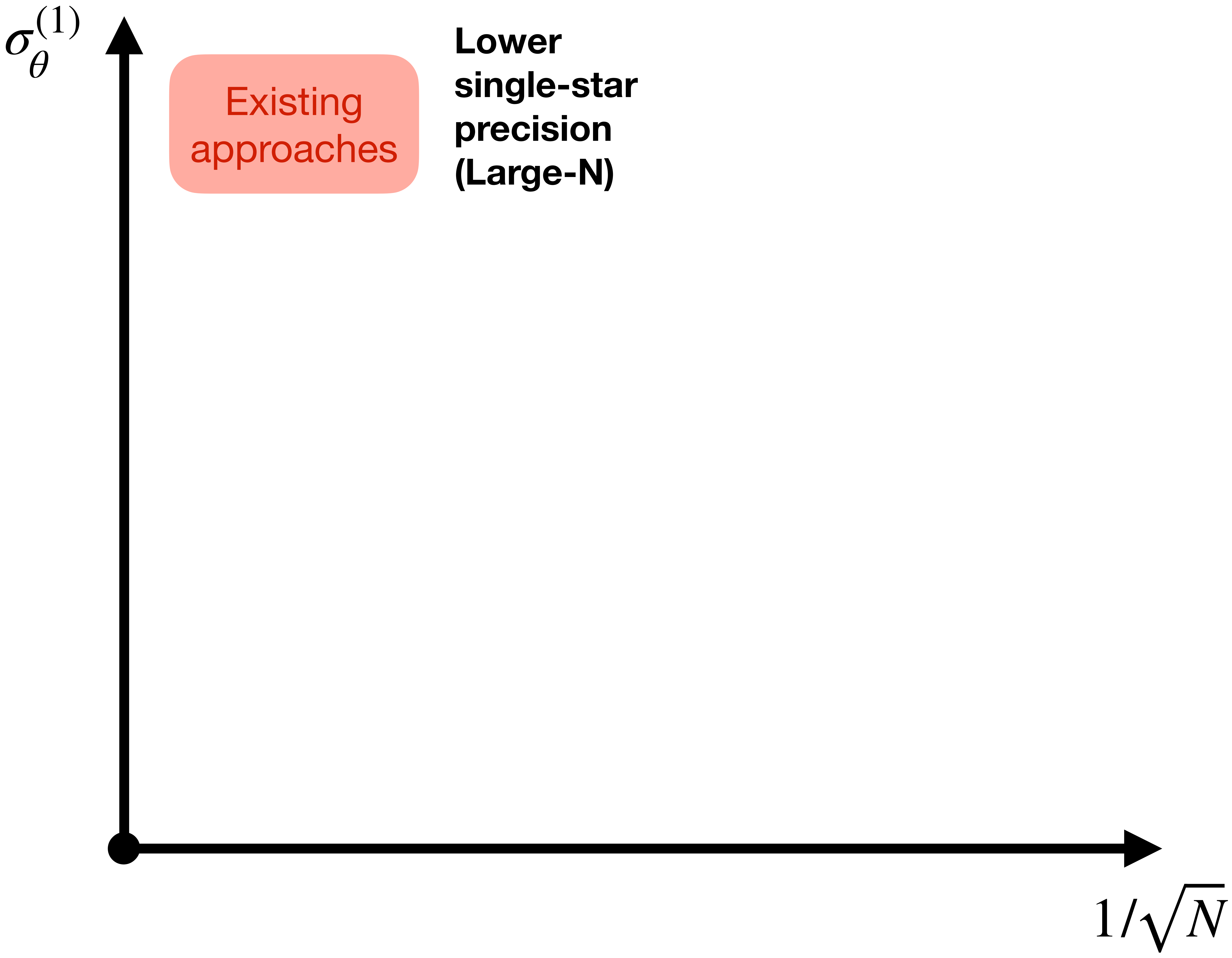
$$\sigma_\theta^{(N)} \sim \frac{\sigma_\theta^{(1)}}{\sqrt{N}}$$

Gets closer, but not quite there…



Moore, Mihaylov, Lasenby, Gilmore. PRL **119** (2017) 261102 [arXiv:1707.06239]

Revisiting astrometric GW detection



Lower single-star precision (Large-N)

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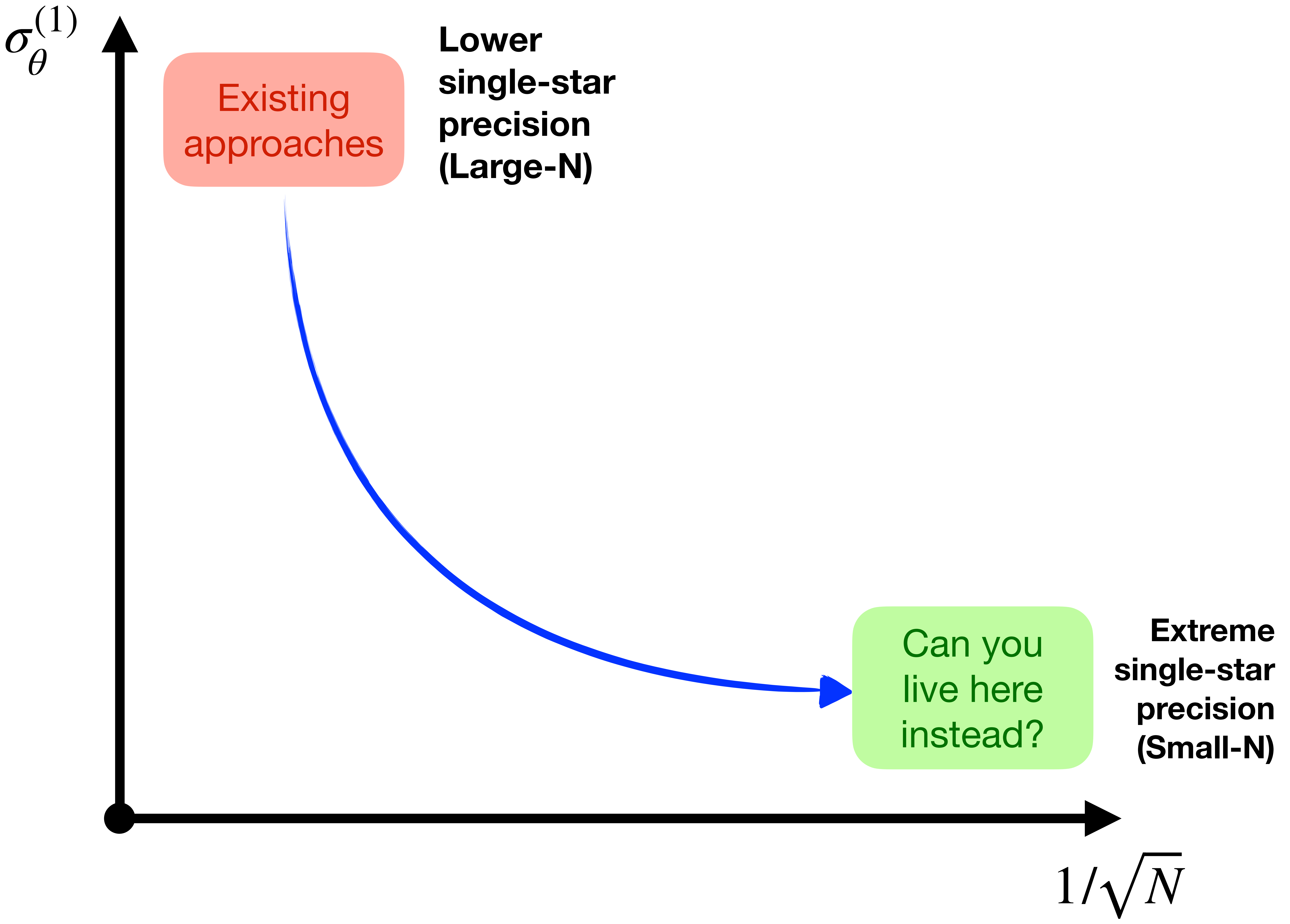

Existing approaches

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Can you live here instead?

Extreme single-star precision (Small-N)

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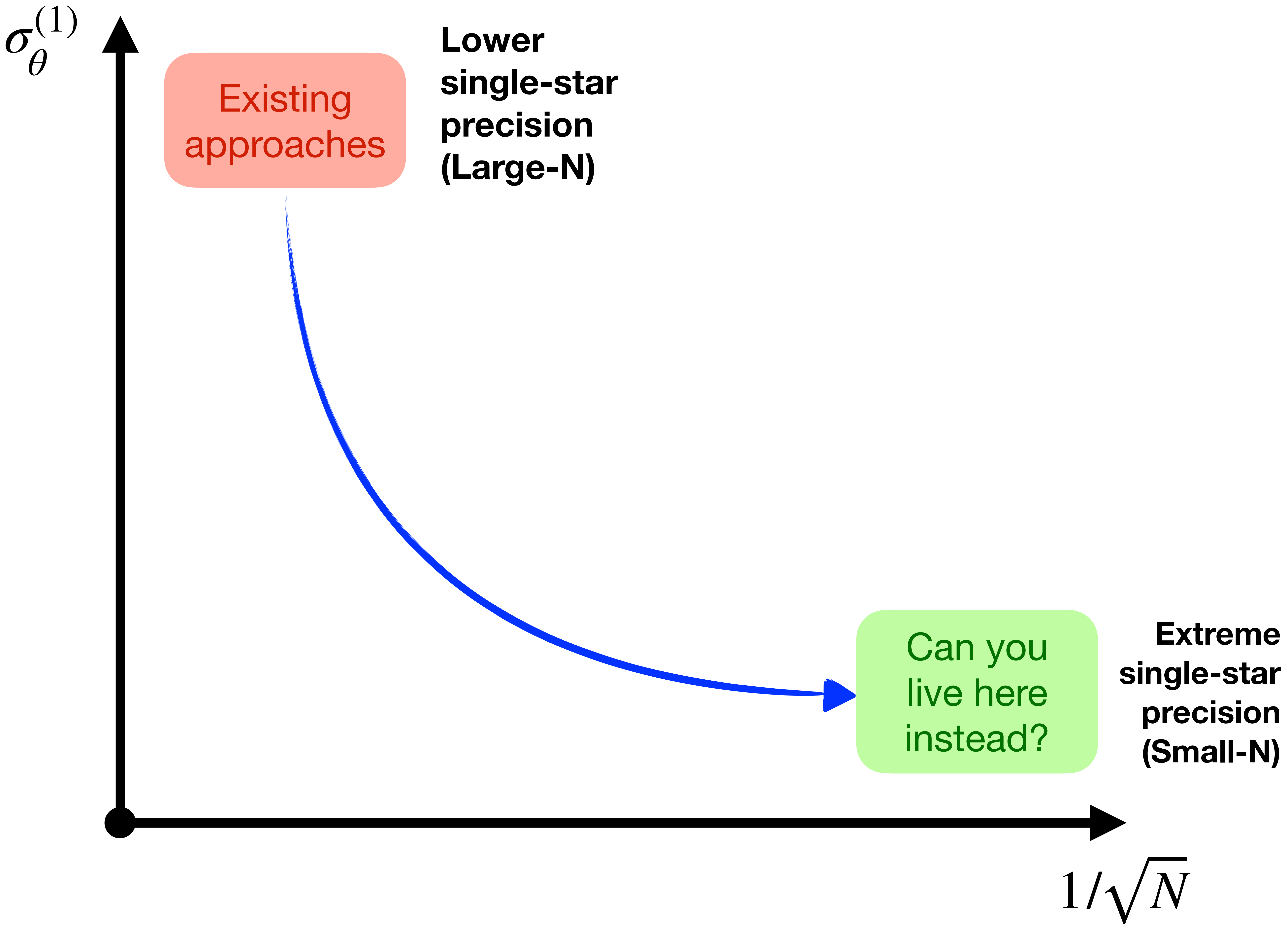

$\sigma_\theta^{(1)}$

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$1/\sqrt{N}$

We study this alternative optimisation

<u>Two classes of issues</u>

Are there sufficiently stable sources to measure?

How would you make the measurement?

Intrinsic source stability

In a time $T_{\rm GW} = 1/f_{\rm GW}$, we need a stellar position to be stable* to $\Delta\theta \leq h_c \sim 10^{-17} \times (\mu{\rm Hz}/f_{\rm GW})$

*deterministic proper motion is OK; this is the limit on the stochastic jitter

A severe constraint: position must not jitter more than ~ few pico-arcseconds over ~10 day periods!

Two types of issues:

- ❖ Jitter in inferred (photometric) position of the star relative to the center of mass
  - ‣ Starspots
- ❖ Jitter in the stellar center of mass
  - ‣ Planets

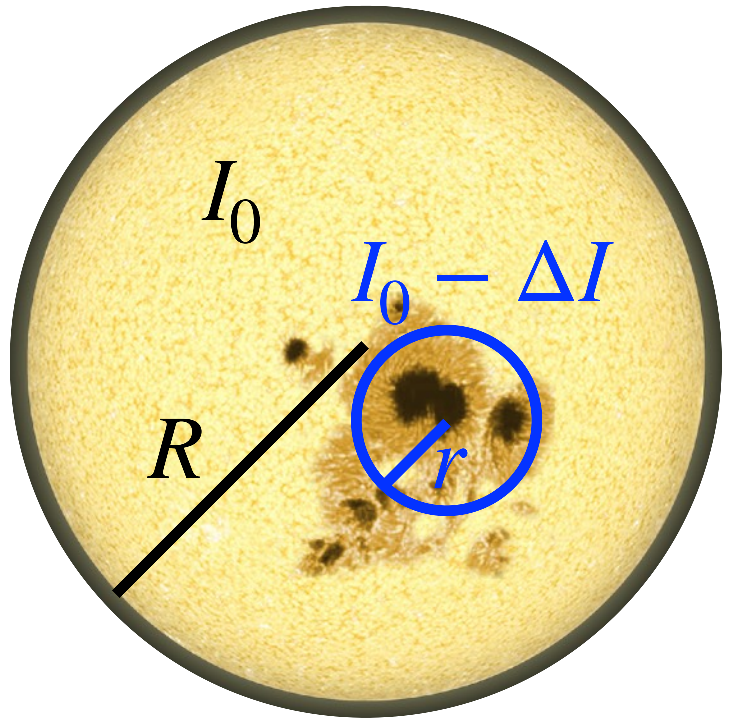
We identify **hot, non-magnetic, photometrically stable white dwarfs (WD) at ~kpc distances** as good targets to overcome these noise sources.

Starspots on WD

$$\Delta\theta_{\text{spot}} \sim \left(\frac{\Delta L}{L_0}\right)_{\text{spot}} \times \frac{R_{\text{WD}}}{d}$$

Hot, photometrically stable WD are ideal!

For $T \sim 2 \times 10^4\,\text{K}$, stellar atmospheres are radiative: spots are suppressed. Also non-magnetic.



Also, visible from large distance: $d \sim 1\,\text{kpc}$.

$R \sim 9 \times 10^3\,\text{km} \sim 10^{-2} R_\odot$ is a typical WD radius for $M \sim 0.6 M_\odot$. Win with smaller size.

Some WD are ***measured* to be photometrically stable** to level of $\Delta L/L_0 \sim 10^{-4}$ on short periods.
Places an upper limit on any possible longer-term change in the starspot configuration at the same level.*

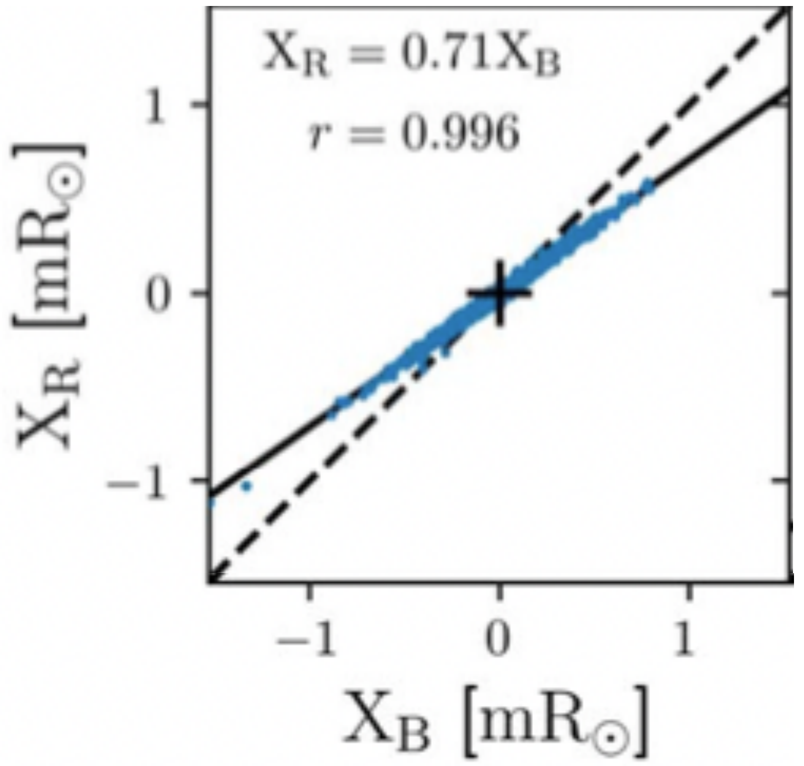
*excluding tuned geometries where the star is viewed almost directly down the rotational axis and the spot is close to the pole

Worst-case jitter limited to

$$\Delta\theta \sim 3 \times 10^{-17}$$

Acceptably small to reach the target strain reach up to $\sim \mu$Hz!

Multi-band noise mitigation techniques could help too Kaplan-Lipkin, *et al.* Astron. J. **163** (2022) 205 [arXiv:2112.06383]



Planetary Reflex Motion

Orbiting bodies directly shift the stellar CoM (stellar reflex motion)

$$(\Delta\theta)_{\text{planet}} \sim \frac{a}{d}\frac{m_{\text{body}}}{M_{\text{star}}}$$

$M_{\text{star}} \sim 0.6 M_{\odot} \sim M_{\text{WD}}$: semi-major axes $0.1\,\text{AU} \lesssim a \lesssim 2\,\text{AU}$ give in-band noise for $10\,\text{nHz} \lesssim f_{\text{GW}} \lesssim 1\,\mu\text{Hz}$.

Demanding $\Delta\theta \lesssim h_c \sim 10^{-17}(\mu\text{Hz}/f_{\text{GW}})$ yields

$$m_{\text{body}} \lesssim 1.5 \times 10^{-8} M_{\odot} \left(\frac{d_{\text{WD}}}{\text{kpc}}\right)\left(\frac{\mu\text{Hz}}{f_{\text{GW}}}\right)^{\frac{1}{3}}\left(\frac{M_{\text{WD}}}{0.6\,M_{\odot}}\right)^{\frac{2}{3}}.$$

Body has radius $r_{\text{body}} \gtrsim 1.3 \times 10^{3}\,\text{km}$ $\qquad$ ($\rho_{\text{body}} \sim 3\,\text{g/cm}^3$)

Very big asteroid / medium-sized moon / minor planet object is a problem.

Are WD OK?

Select for clean WD, use mitigations

See our paper for an extensive list of references on this topic

Roughly half of WD have evidence of recent / active / past accretion of rocky material.
(IR excess, metal absorption lines, gaseous emission lines, gaseous absorption lines, complex transits, Si absorption lines in WD atmosphere)

Consensus understanding: complicated post-AGB system evolution (AGB mass-loss event resets dynamical age)

Current amounts of material in photospheres are much less than the problematic object ($10^{-8}M_{\odot}$).

BUT: Accretion can herald other, more stably orbiting, problematically large bodies in system.

Use **accretion evidence as a veto criterion** to try avoid such systems: other WD are much cleaner!

If planet still present, blinds narrow frequency ranges: orbital motion very stable on $\sim 10\,\mathrm{yr}$ mission timescales.

Omit one star at a time to check if putative signal is common (GW) or single-star (e.g., a planet).

Motion induced by planet also not exactly degenerate with a GW source. Presumably allows some discrimination; needs modelling.

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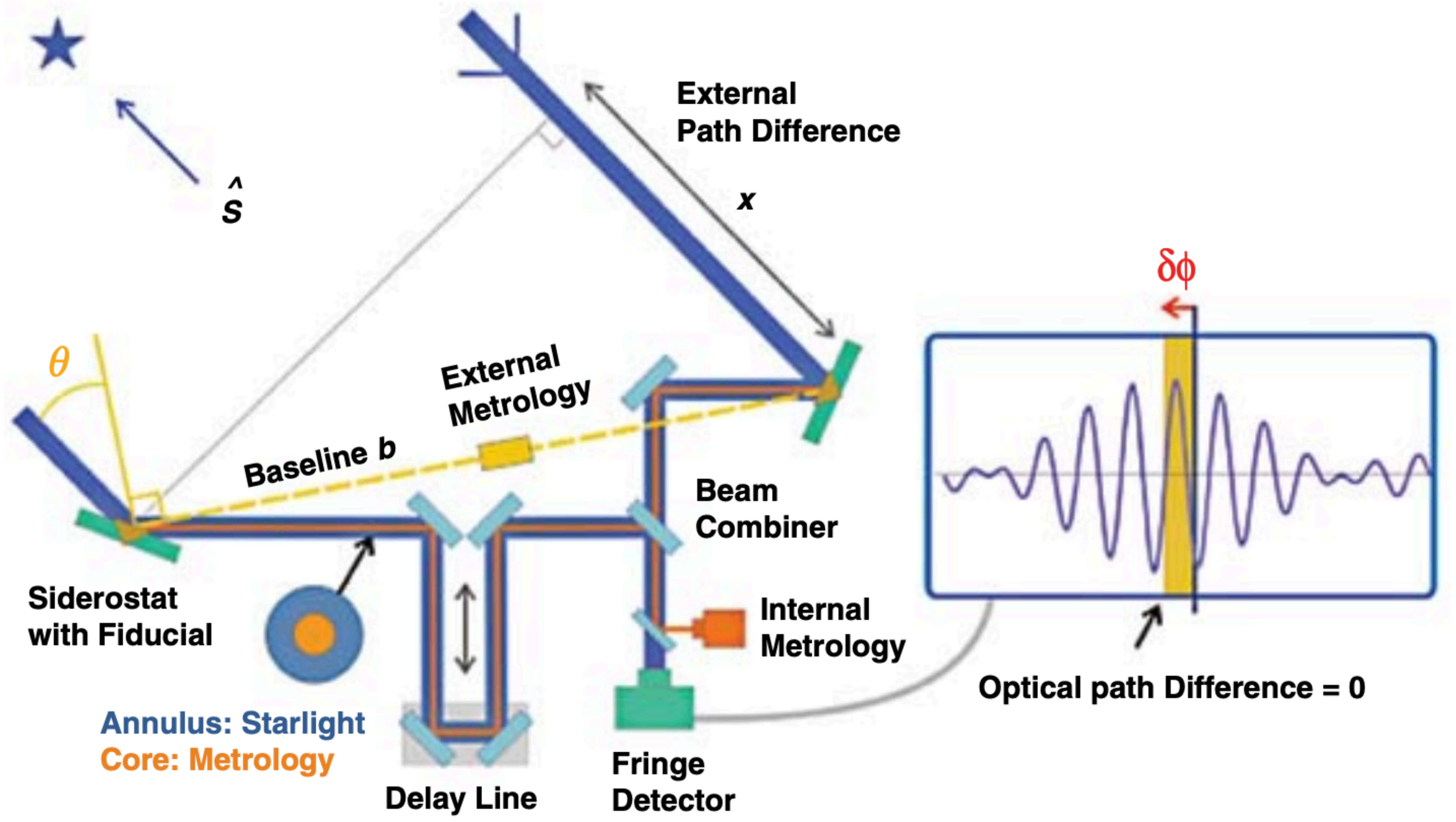
WDs STILL LOOK ATTRACTIVE AS A CLASS OF TARGETS!
…although some specific WD may be problematic

Stellar Interferometry I

So how do you measure an angle to pico-arcsecond accuracy?

Space-based stellar interferometry with active baseline metrology.



SIM Lite Astrometric Observatory: From Earth-Like Planets to Dark Matter (NASA, 2009)

<u>Measure 3 things:</u>

(1) baseline length (external metrology)

(2) internal optical path lengths (internal metrology)

(3) location of the maximum contrast in the interference pattern as internal delay is scanned (zero path-length difference)

Knowing (2) and (3) gives you
$x = b \cdot \hat{s} = b \sin\theta$
Knowing (1) then gives you θ

Mission parameters I

$$(\Delta\theta)_{\text{astrometric}} \sim \frac{\lambda}{B\sqrt{N_\gamma}} \sim \frac{\lambda}{B}\frac{1}{\sqrt{F_0 A \tau}}$$

To compare with characteristic strain, $\tau \sim T_{\text{GW}}$.
Take $\lambda \sim \lambda_{\text{Wien}} \sim 0.14\,\mu\text{m}$, $F_0 \sim (\pi^2/60)T^4(R/d)^2/E_\gamma \sim 560\,\text{m}^{-2}\text{s}^{-1}$:

$$h_c \sim 3 \times 10^{-17} \times \sqrt{\frac{A_{\text{Hubble}}}{A}} \times \left(\frac{90\text{km}}{B}\right) \times \sqrt{\frac{f_{\text{GW}}}{\mu\text{Hz}}}$$

Need a **90km baseline,** and **Hubble-sized collectors** (2.4m diameter)**.**

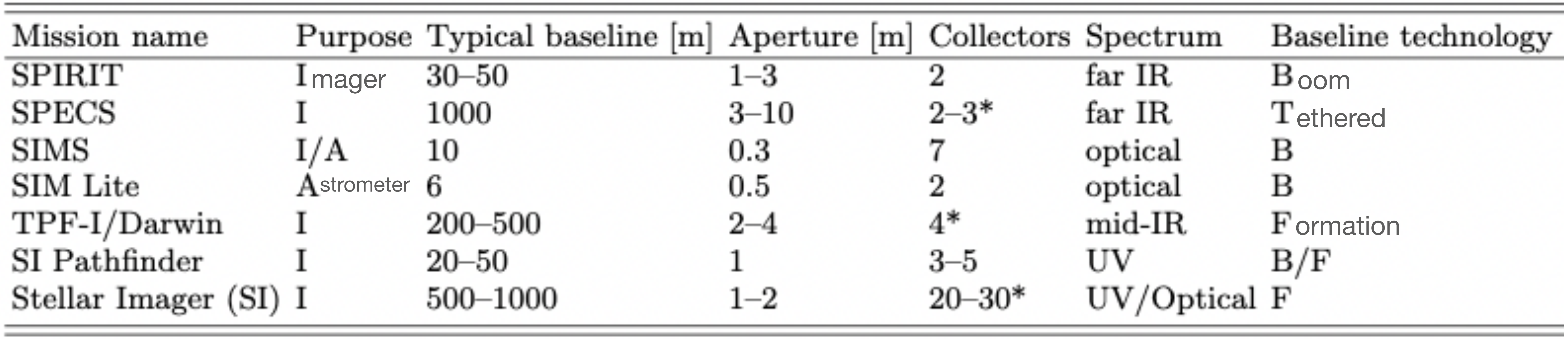
Separate, formation-flown collector spacecraft.

Tradespace exists to optimise parameter choices: larger baseline for smaller mirrors, etc.

Restrict $\lambda/B \gtrsim R/d$ for unsuppressed interference fringe contrast: $B \lesssim 480\,\text{km}$.

Mission parameters II

2000s-era mission studies contemplated missions in this class! Shorter baselines, but space is free.



Mission name	Purpose	Typical baseline [m]	Aperture [m]	Collectors	Spectrum	Baseline technology
SPIRIT	Imager	30–50	1–3	2	far IR	Boom
SPECS	I	1000	3–10	2–3*	far IR	Tethered
SIMS	I/A	10	0.3	7	optical	B
SIM Lite	Astrometer	6	0.5	2	optical	B
TPF-I/Darwin	I	200–500	2–4	4*	mid-IR	Formation
SI Pathfinder	I	20–50	1	3–5	UV	B/F
Stellar Imager (SI)	I	500–1000	1–2	20–30*	UV/Optical	F

* plus a dedicated combiner

Many of these were more technologically complicated, synthetic-aperture imagers.

All-new, GW-science motivation for space-based instruments of this type!

<u>Additional requirements:</u>

- one pair of collectors for each star (min. 4 collectors for the min. 2 stars required for real-time relative angular measurement)
- metrology and light-passing optics; modest: 1W-class lasers, 15-cm class optical elements

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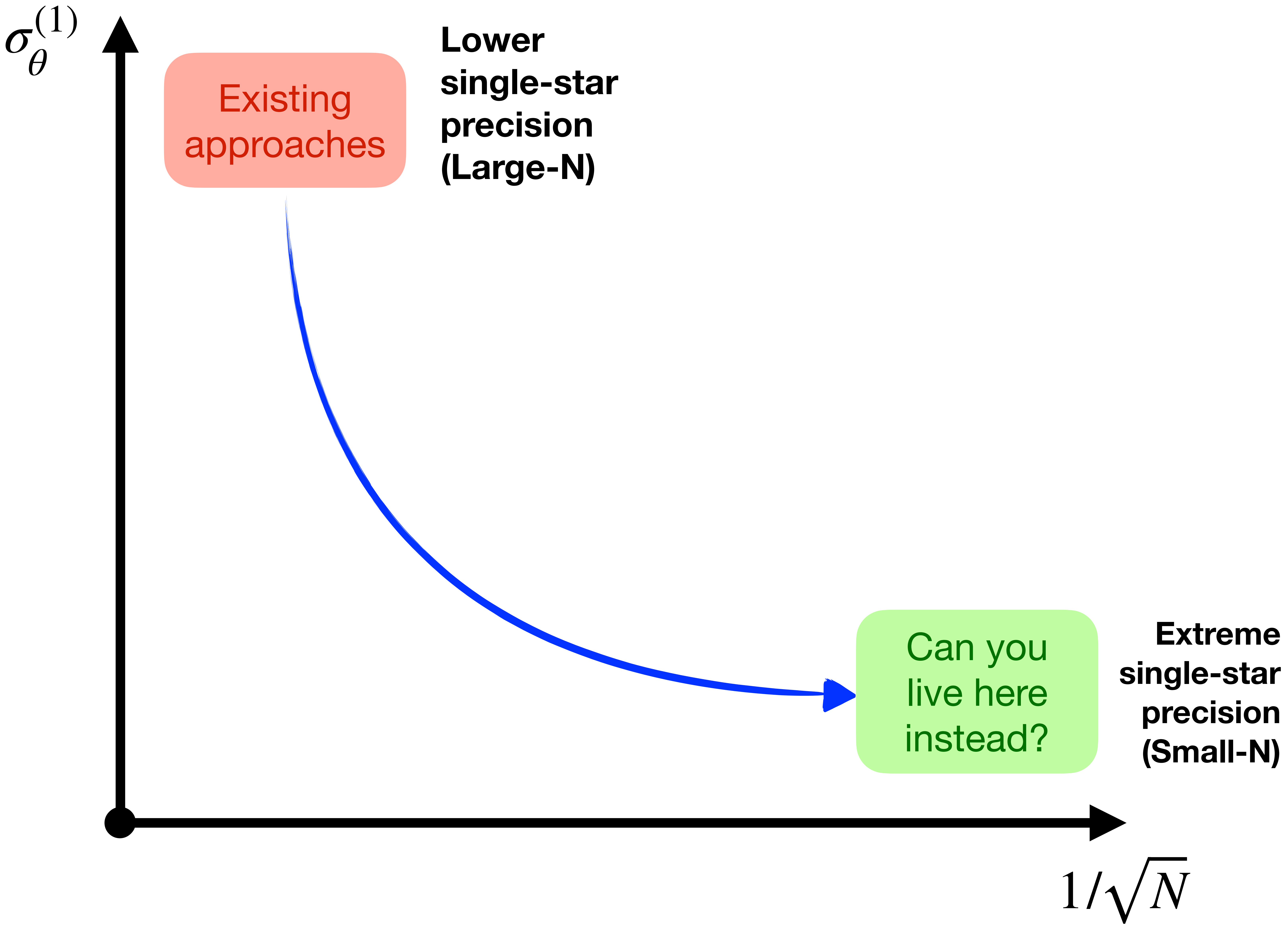

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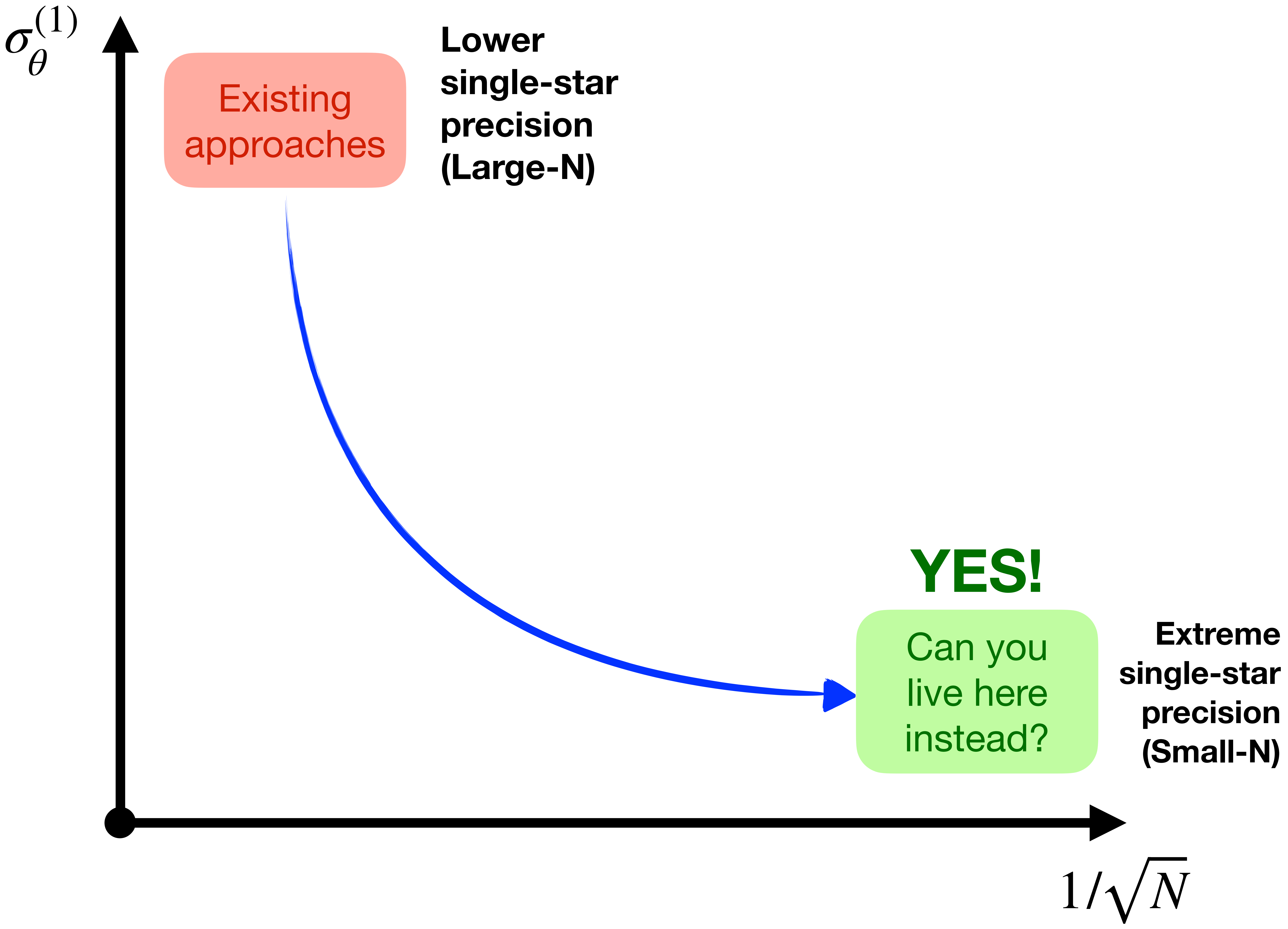

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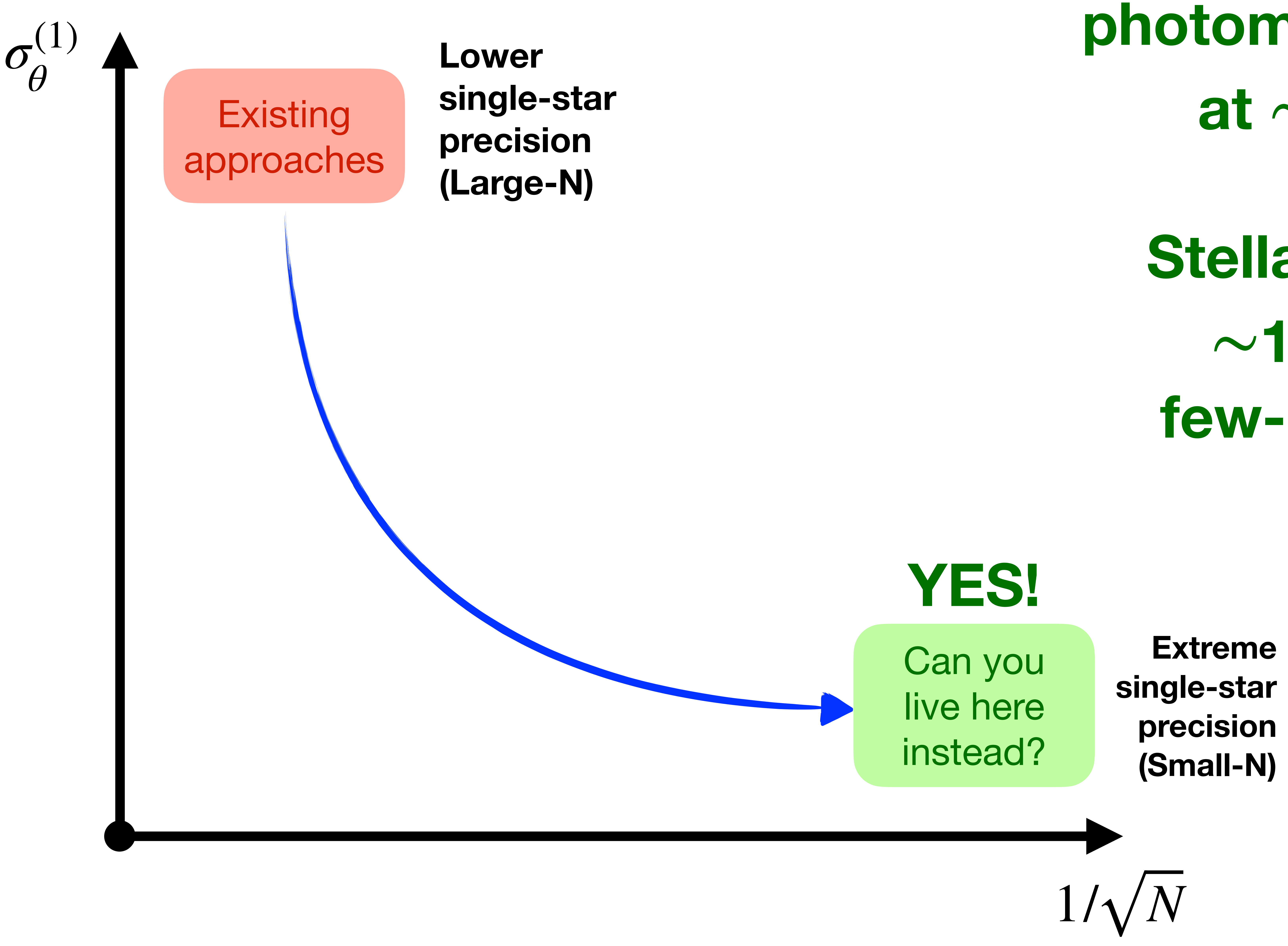

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Stellar interferometry:
∼100km baseline
few-meter collectors

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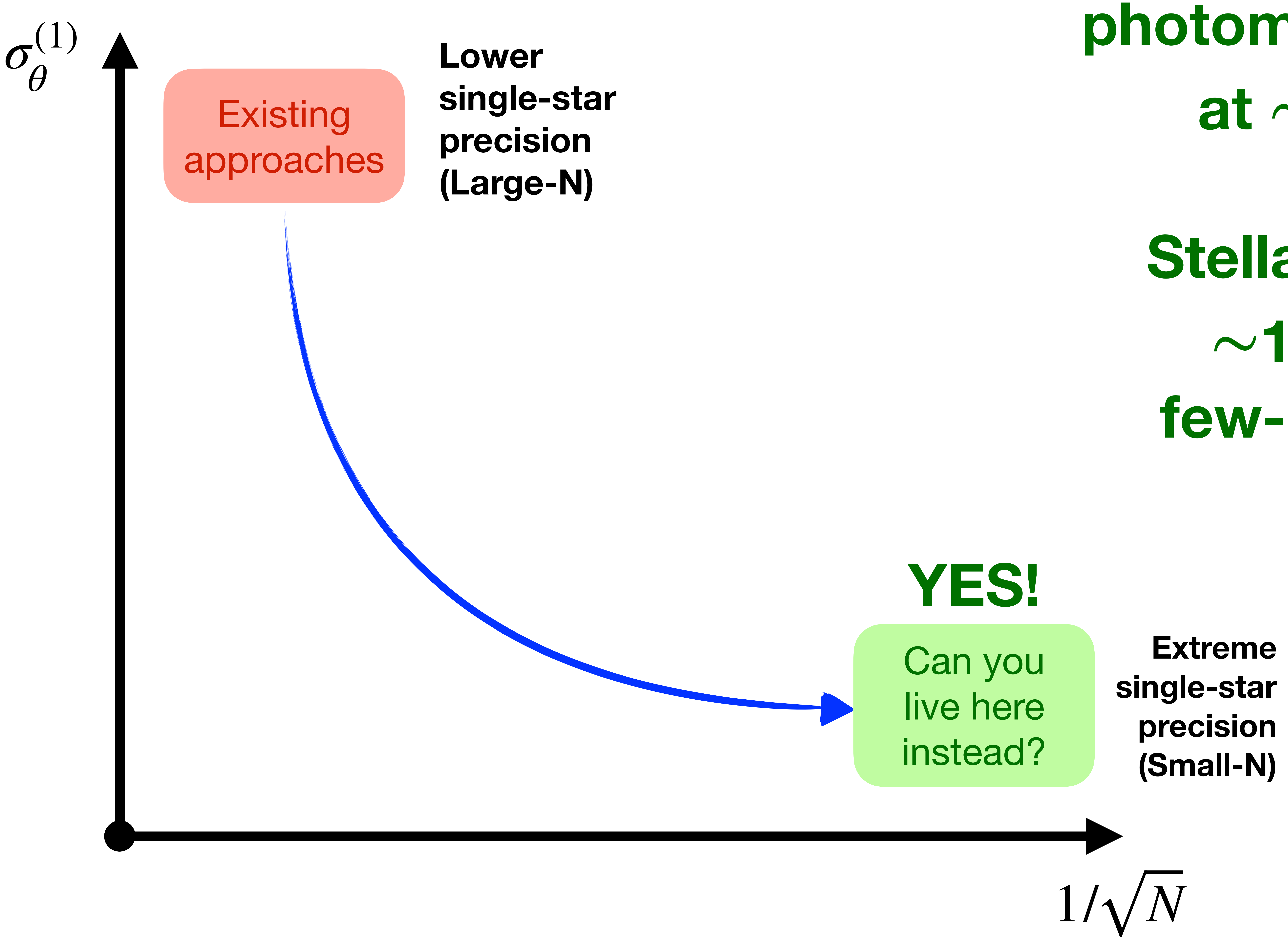

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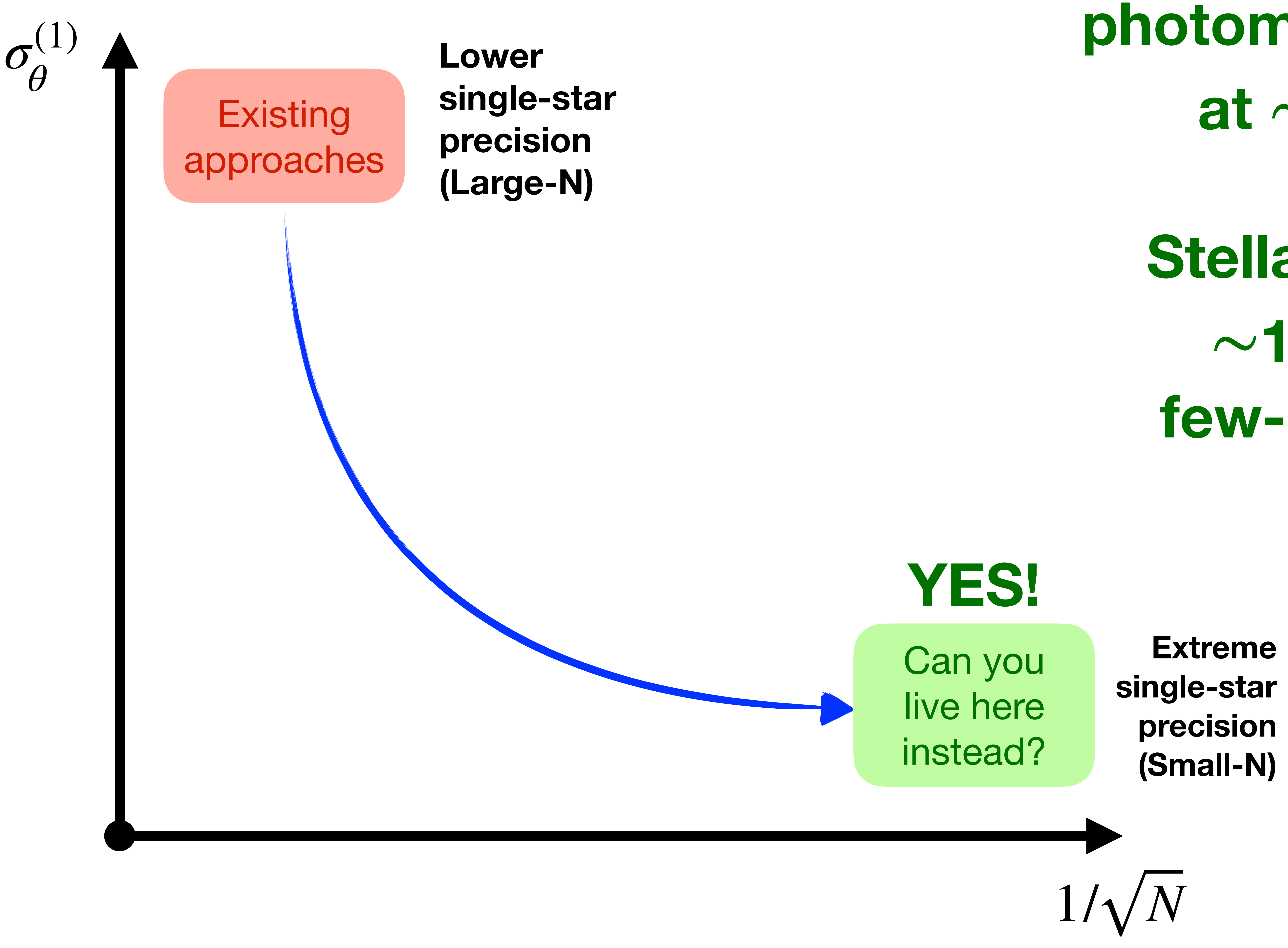

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