Astrometric GW Detection via Stellar Interferometry

TeVPA 2022

Queen's University
Kingston, ON, Canada

August 11, 2022

M.A.F., P. W. Graham, B. Macintosh, S. Rajendran. Phys. Rev. D **106**, 023002 (2022) [2204.07677].

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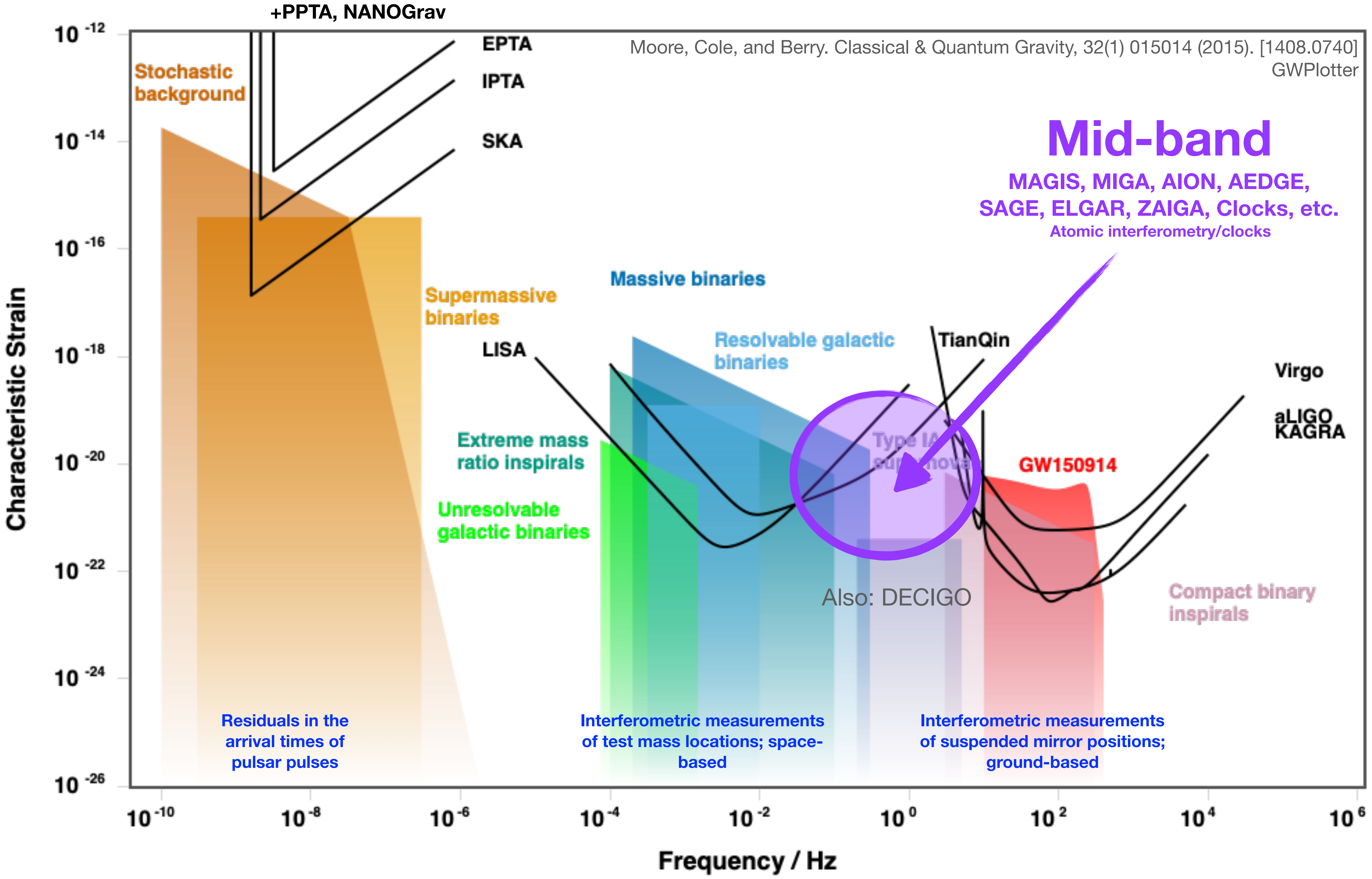
JOHNS HOPKINS
UNIVERSITY

GW Detection Landscape


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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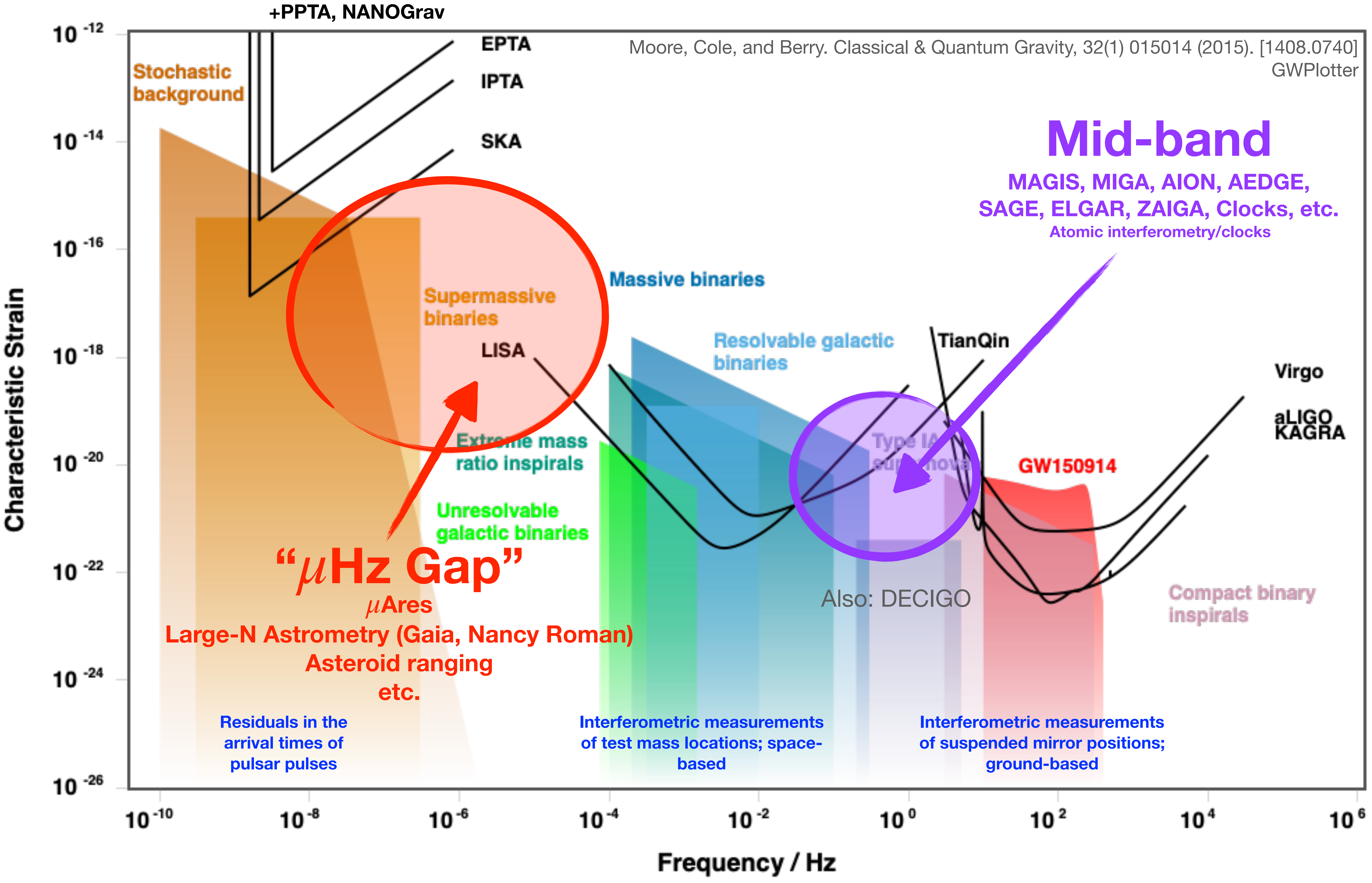

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“μHz Gap”

μAres

Large-N Astrometry (Gaia, Nancy Roman)

Asteroid ranging

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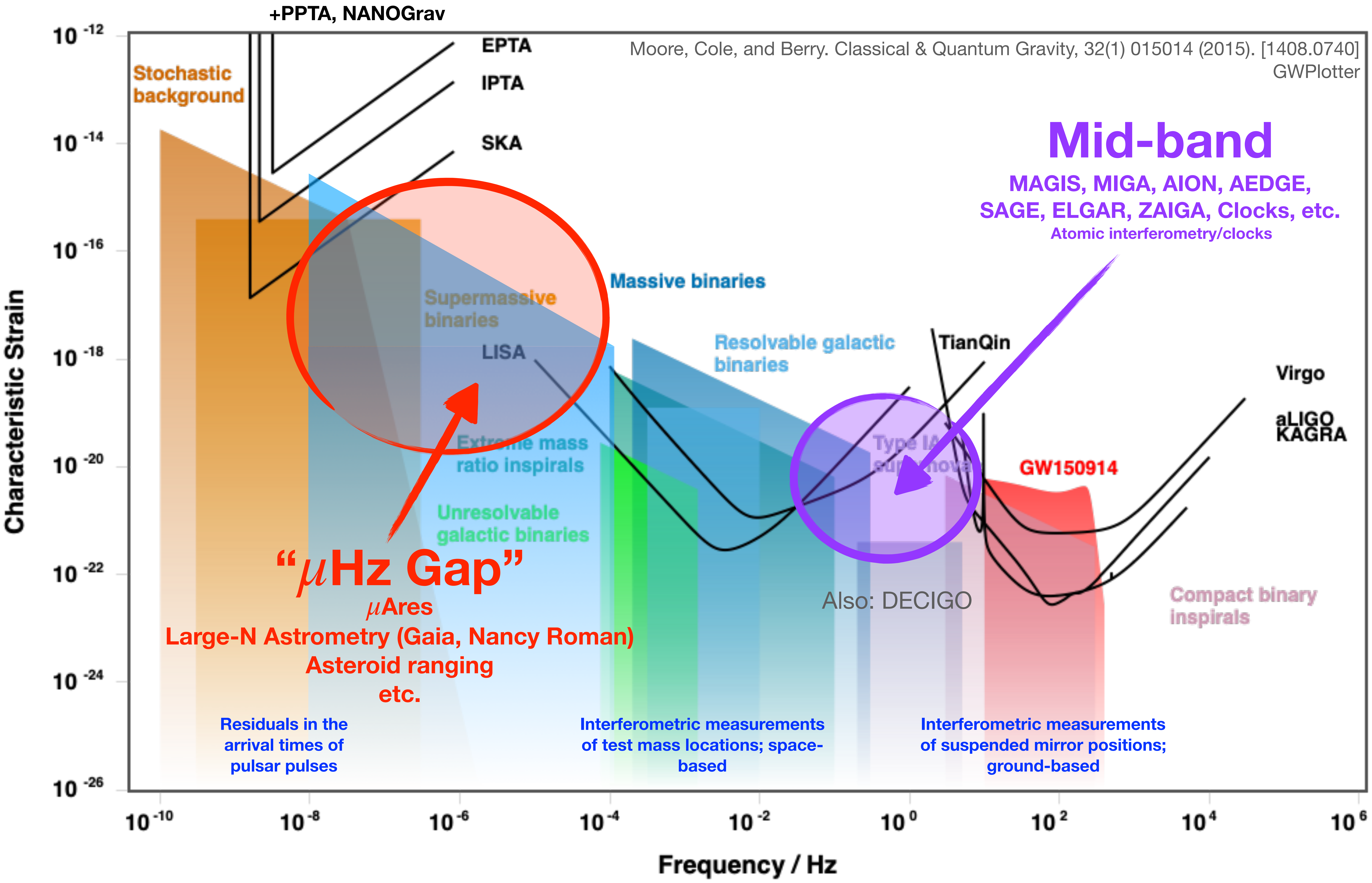

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The “μHz Gap”

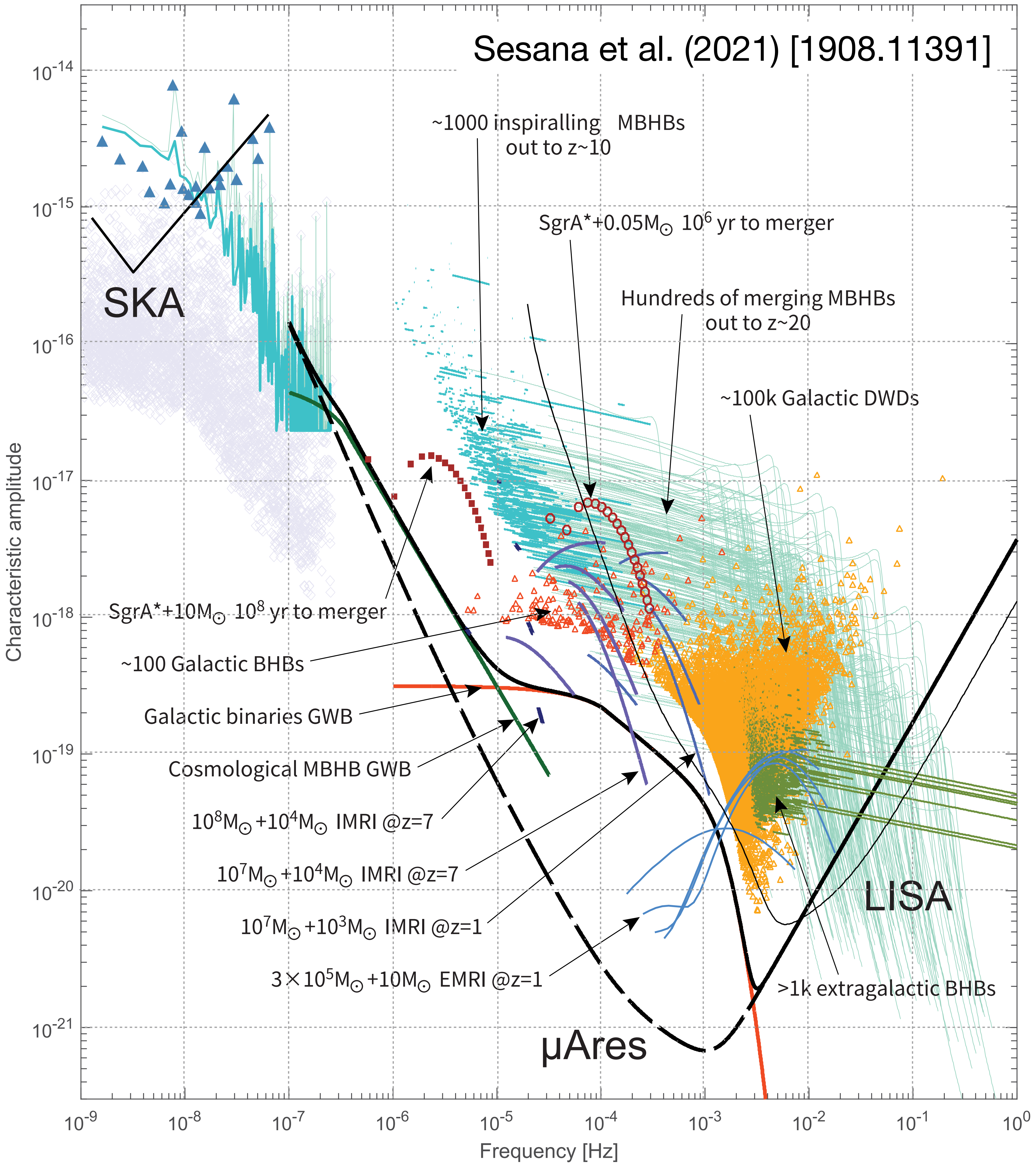
Interesting sources:

- Galactic black hole binaries (BHBs)
- Cosmologically distant massive binary black holes (MBHBs)
- $10 M_\odot$ 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



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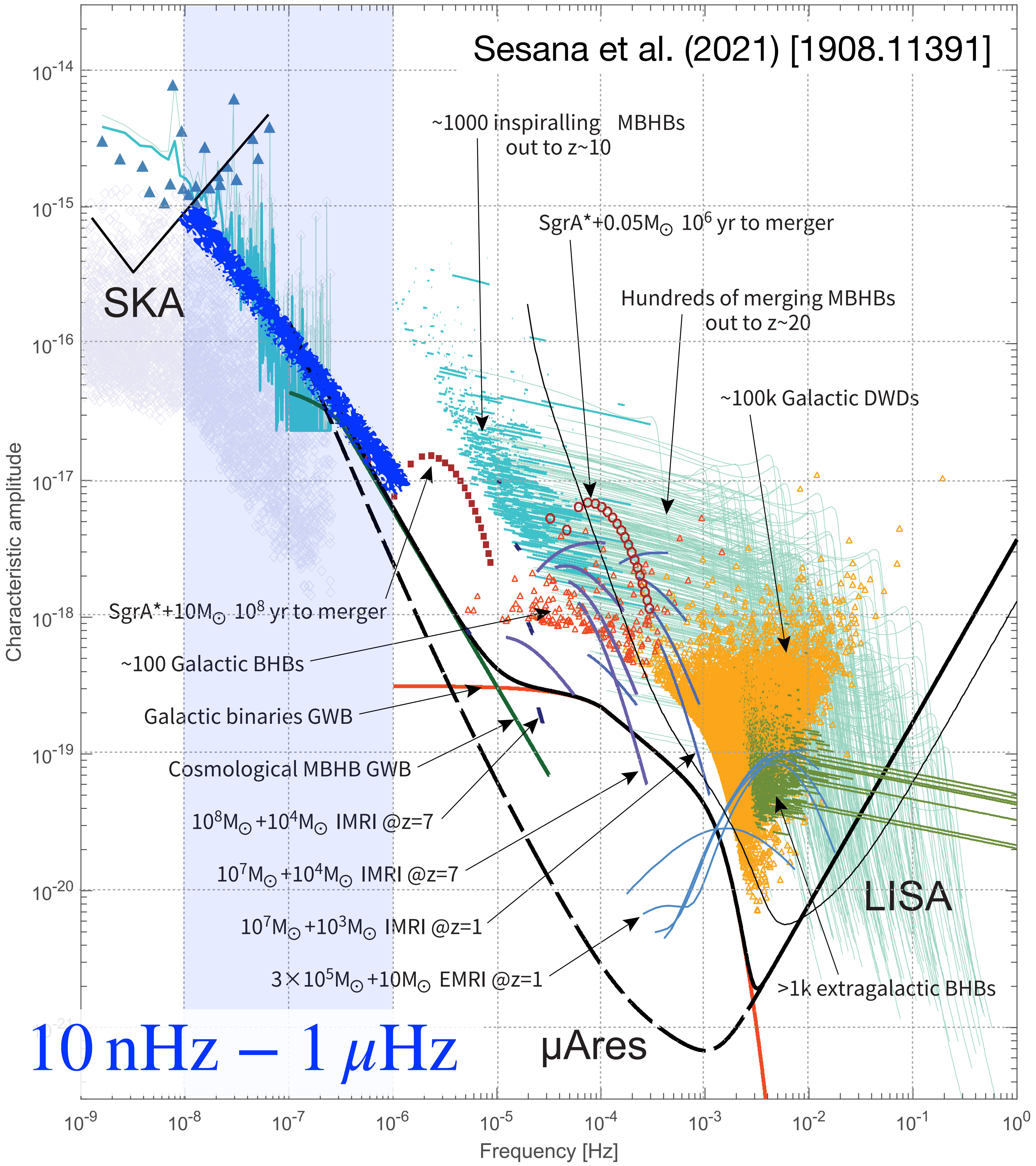
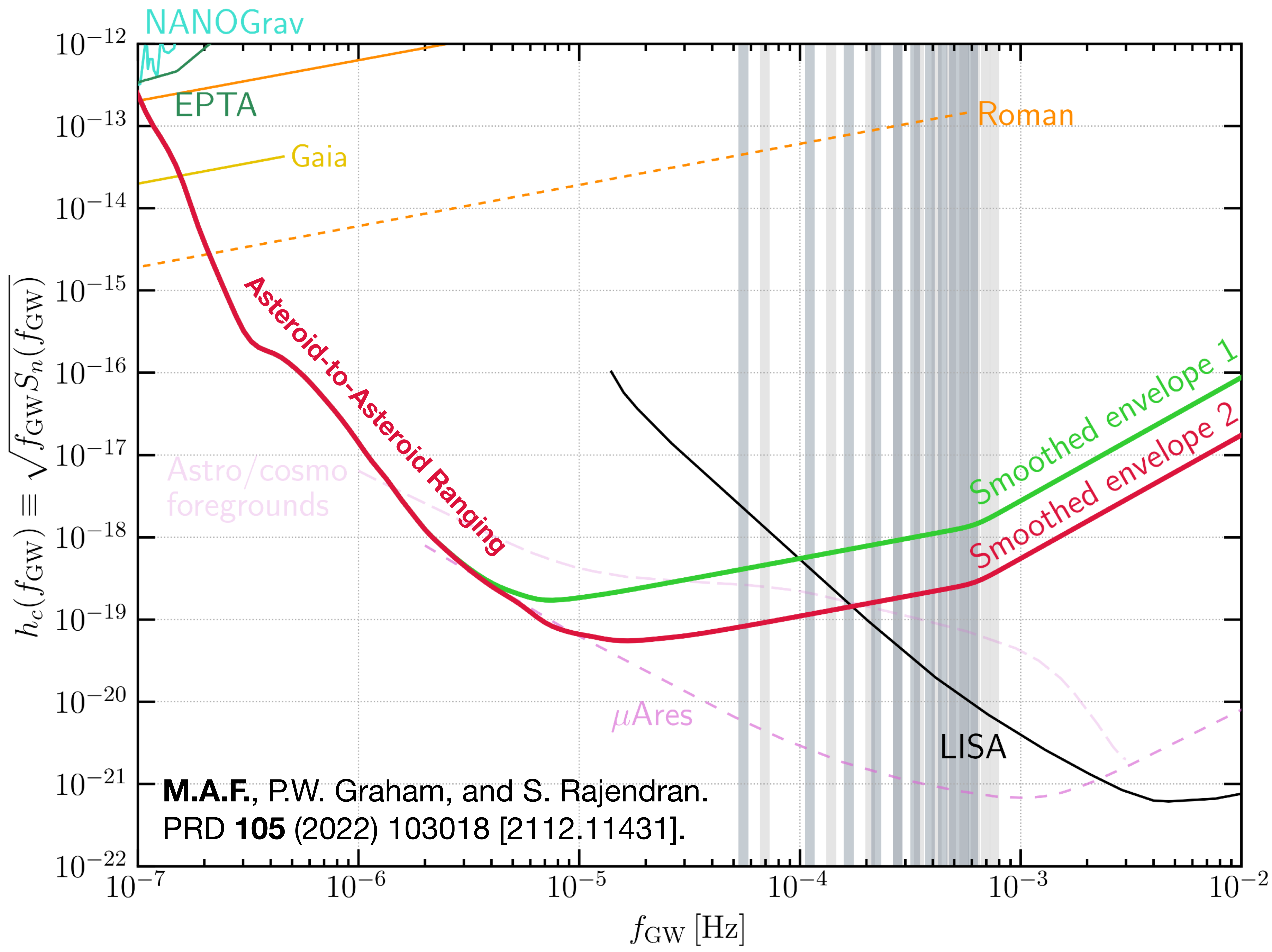


Existing approaches in this band



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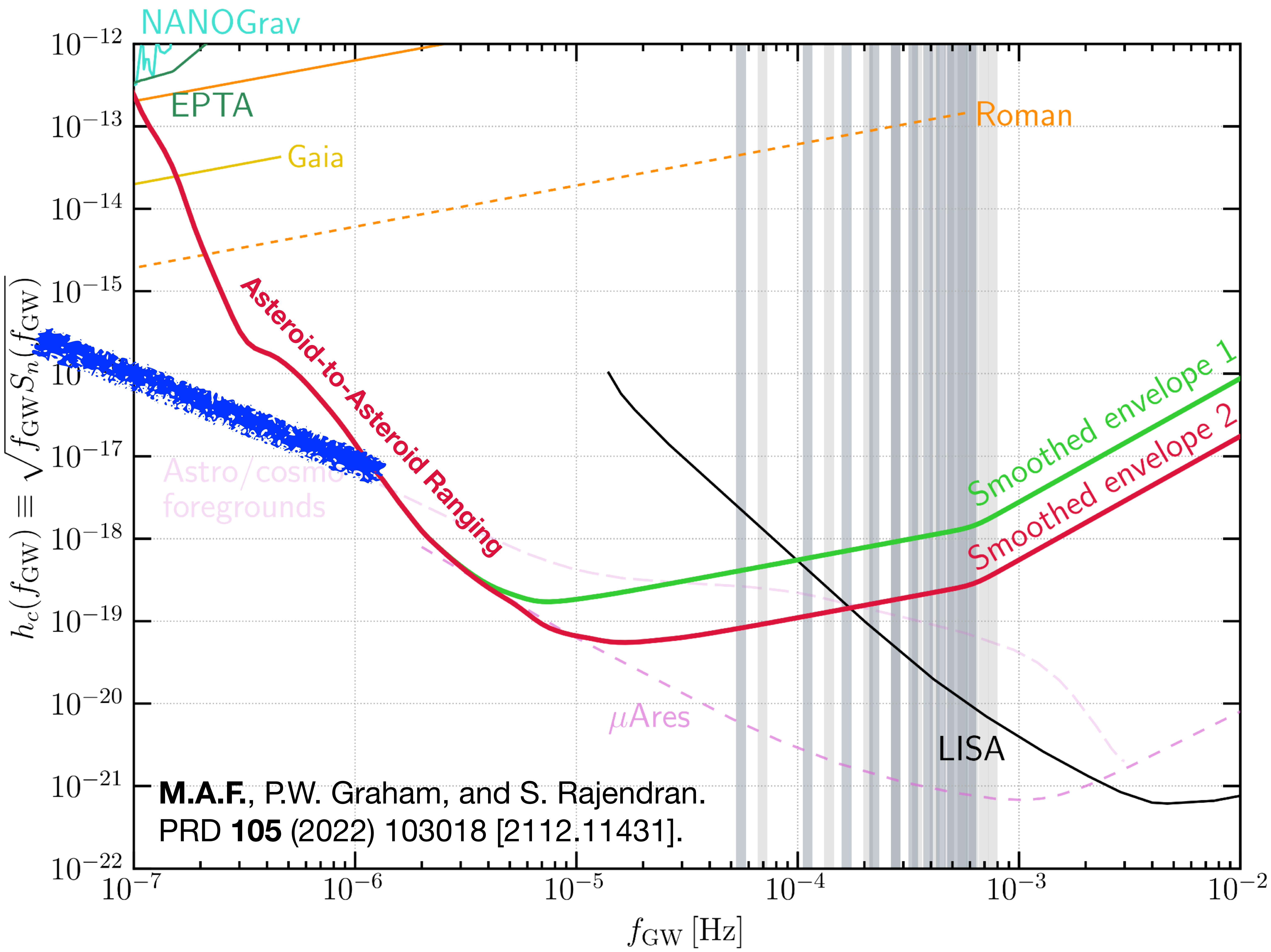

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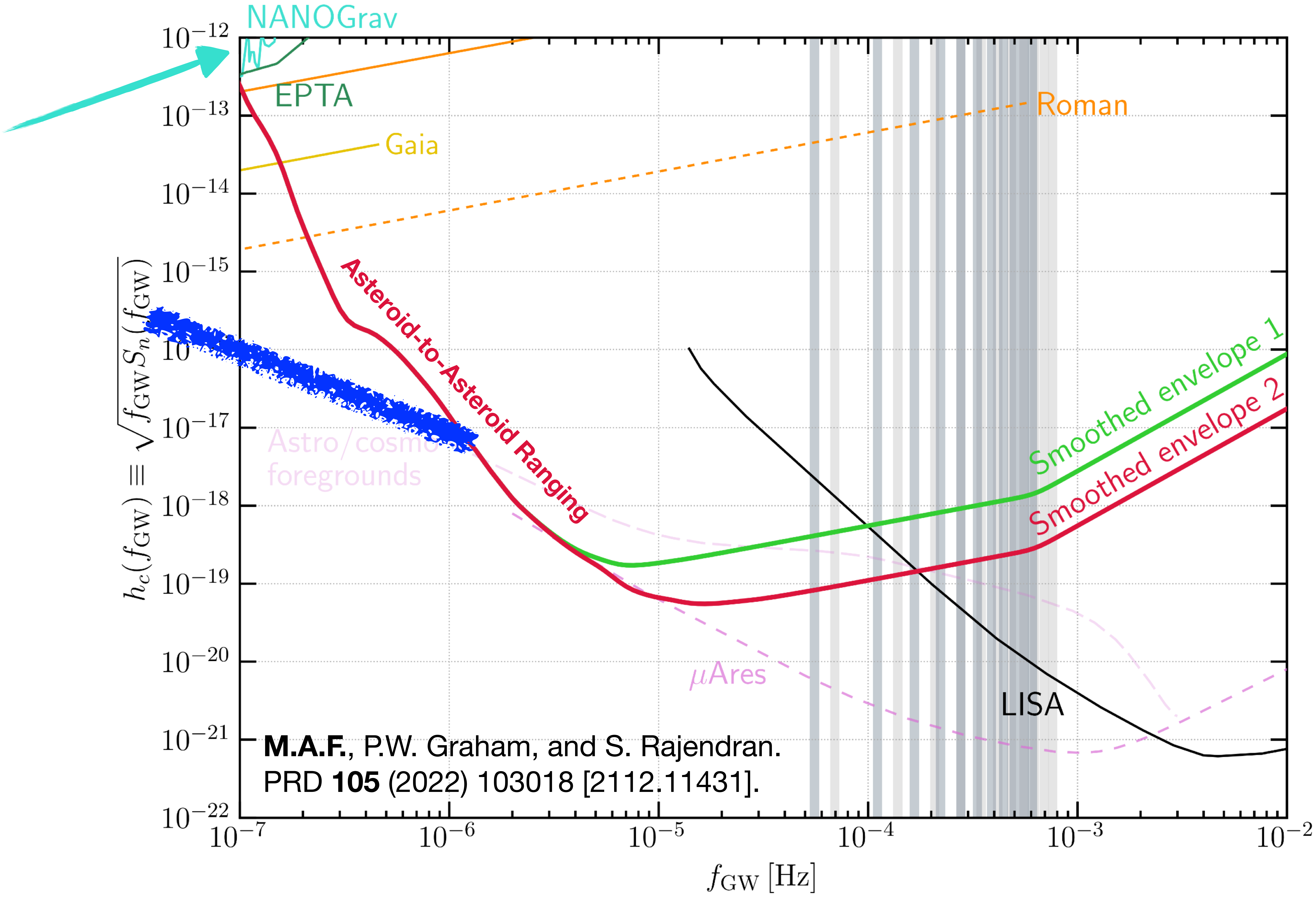

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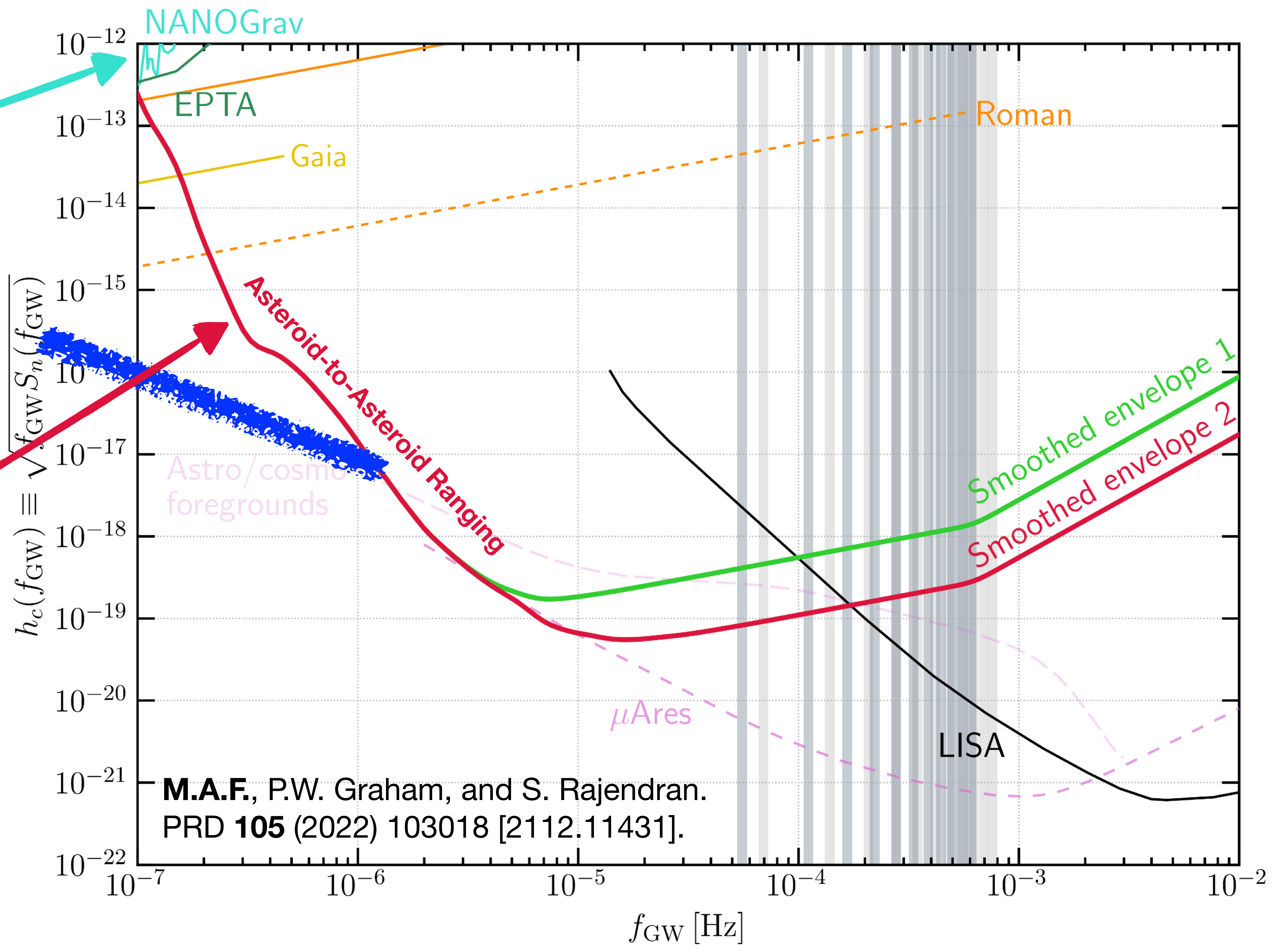

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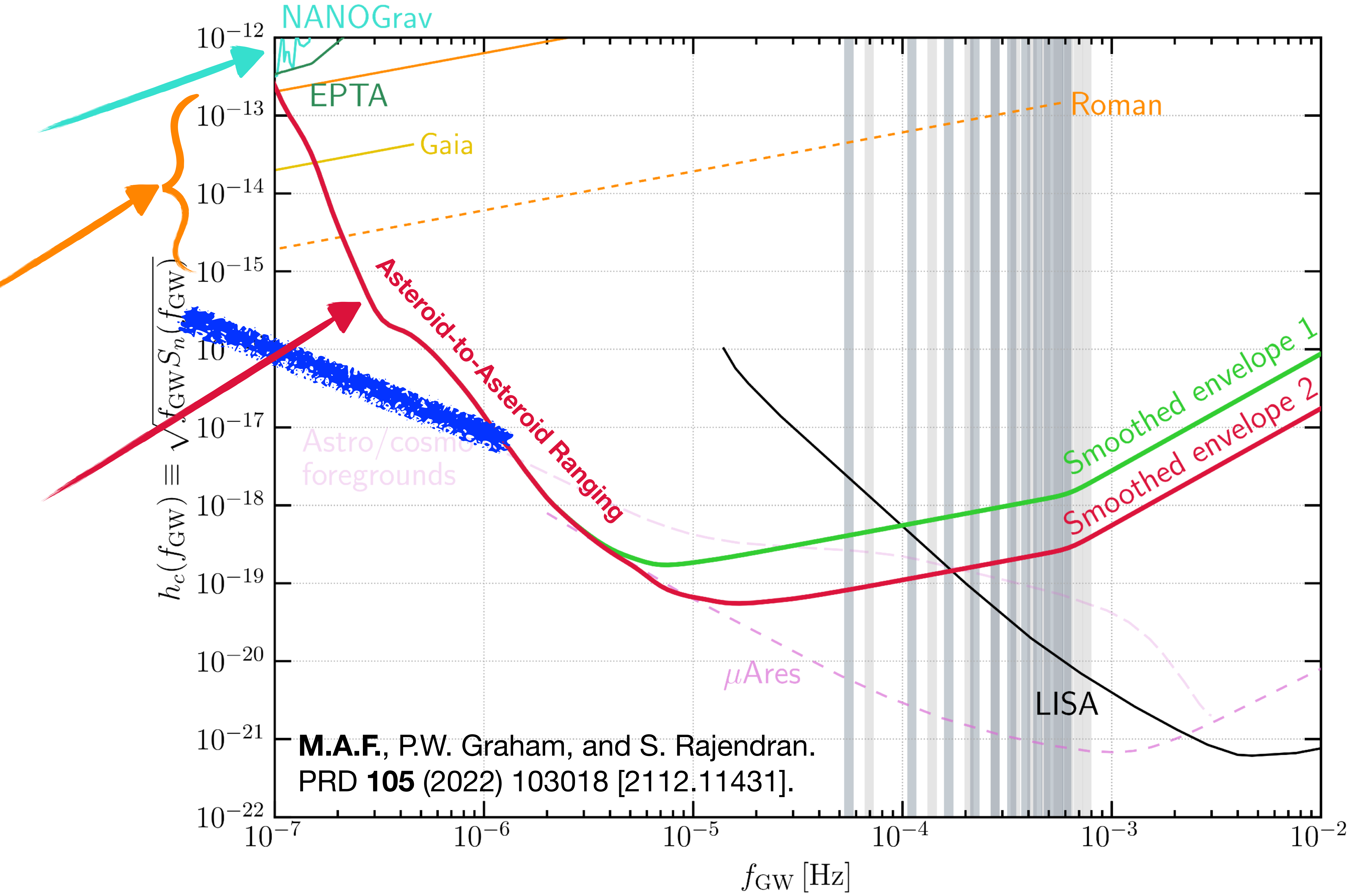

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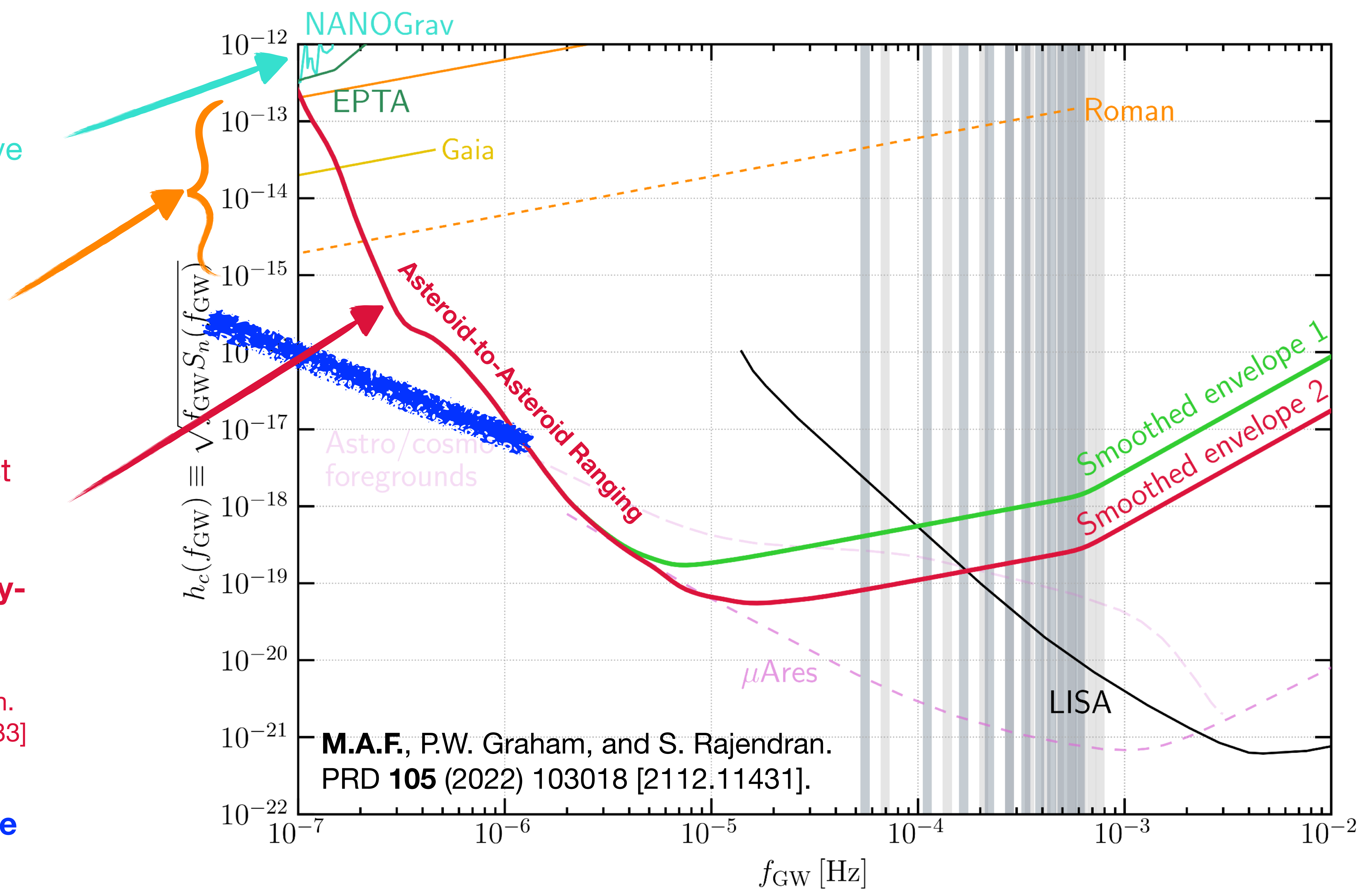
So how can we reach the required sensitivity?



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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

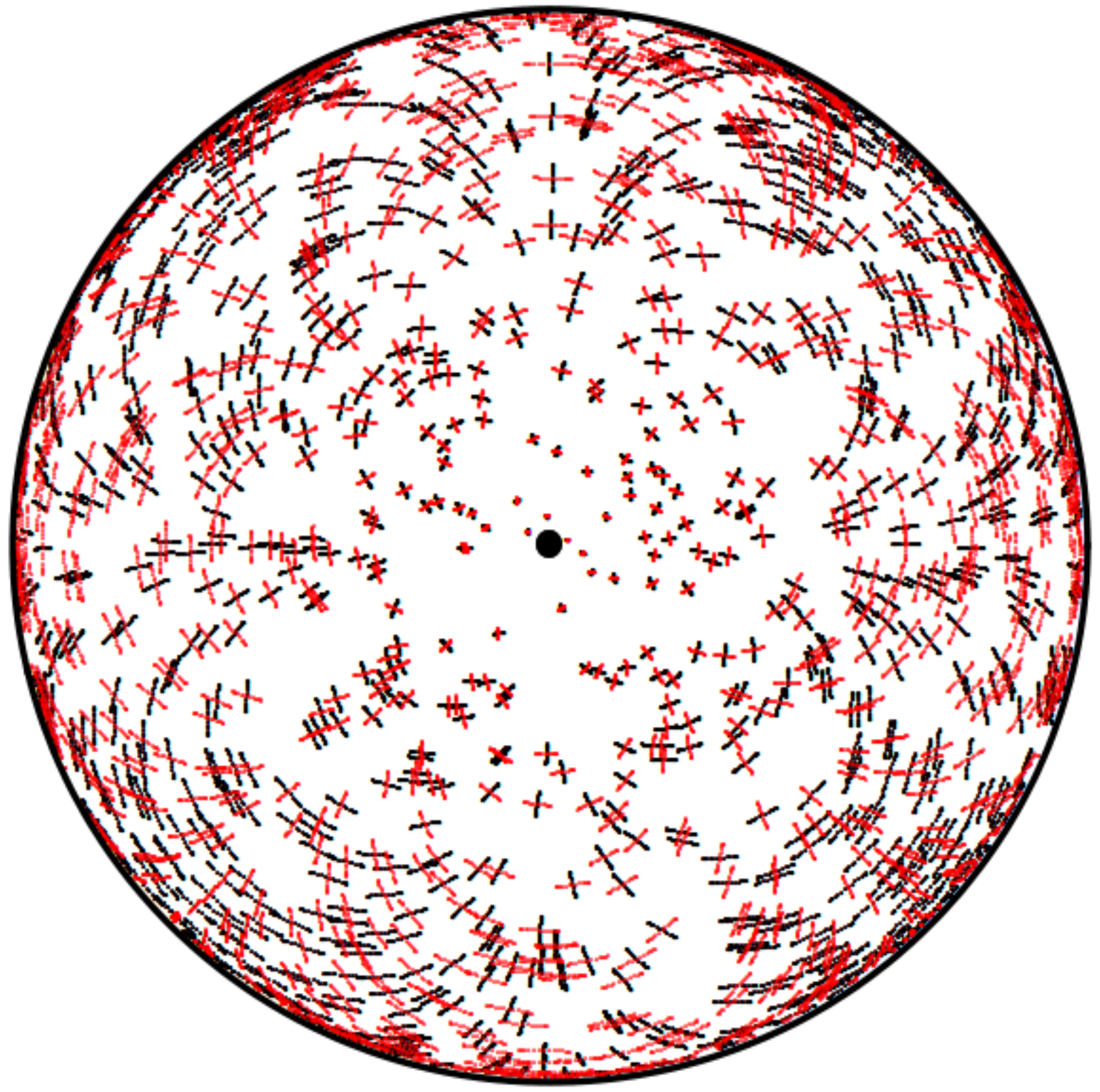
Extremely large-N surveys (Gaia, Roman Space Telescope)

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

Exploit large-N statistics:

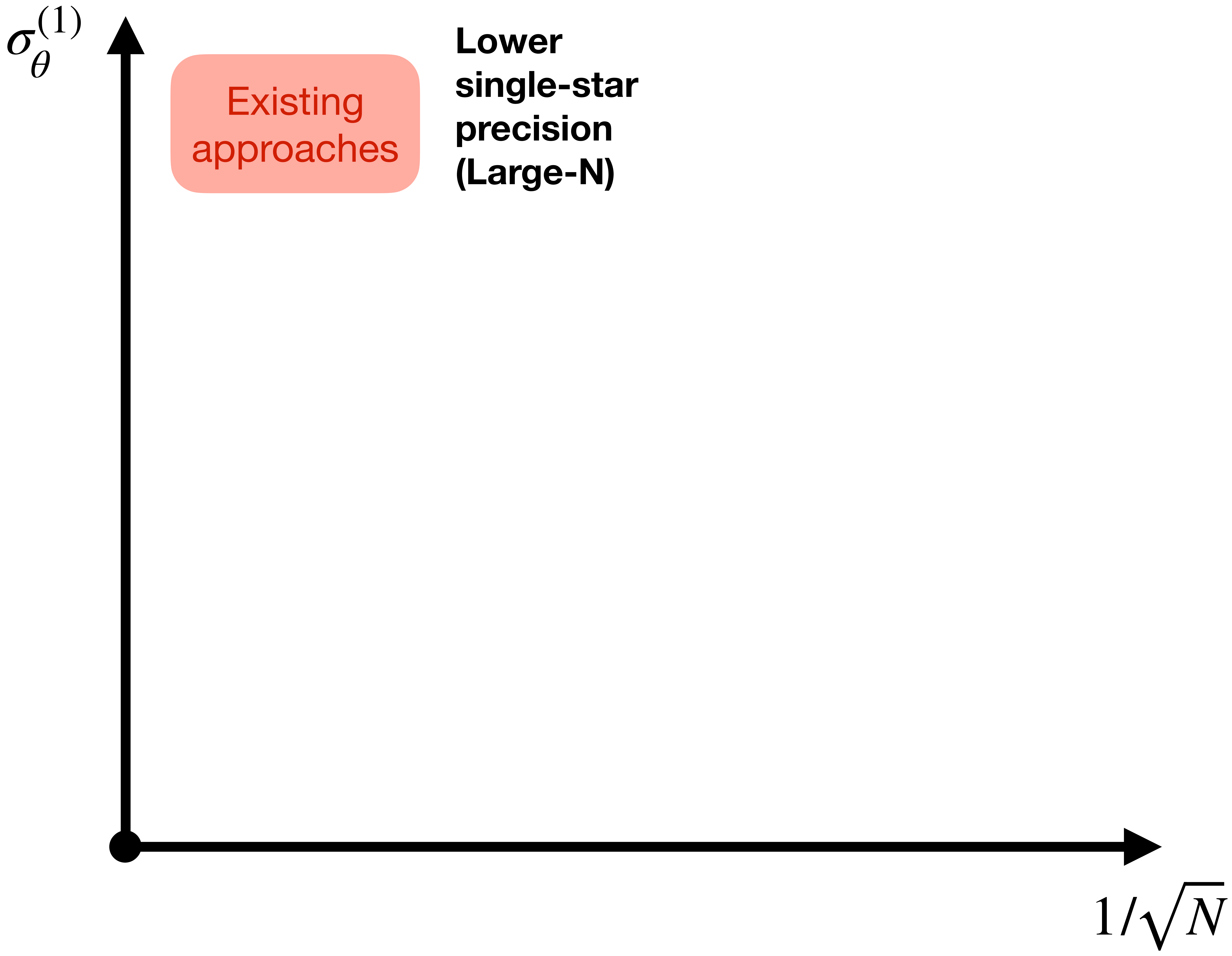
$$\sigma_\theta^{(N)} \sim \frac{\sigma_\theta^{(1)}}{\sqrt{N}}$$

Gets closer, but not quite there…



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

Revisiting astrometric GW detection



Existing approaches

Lower single-star precision (Large-N)

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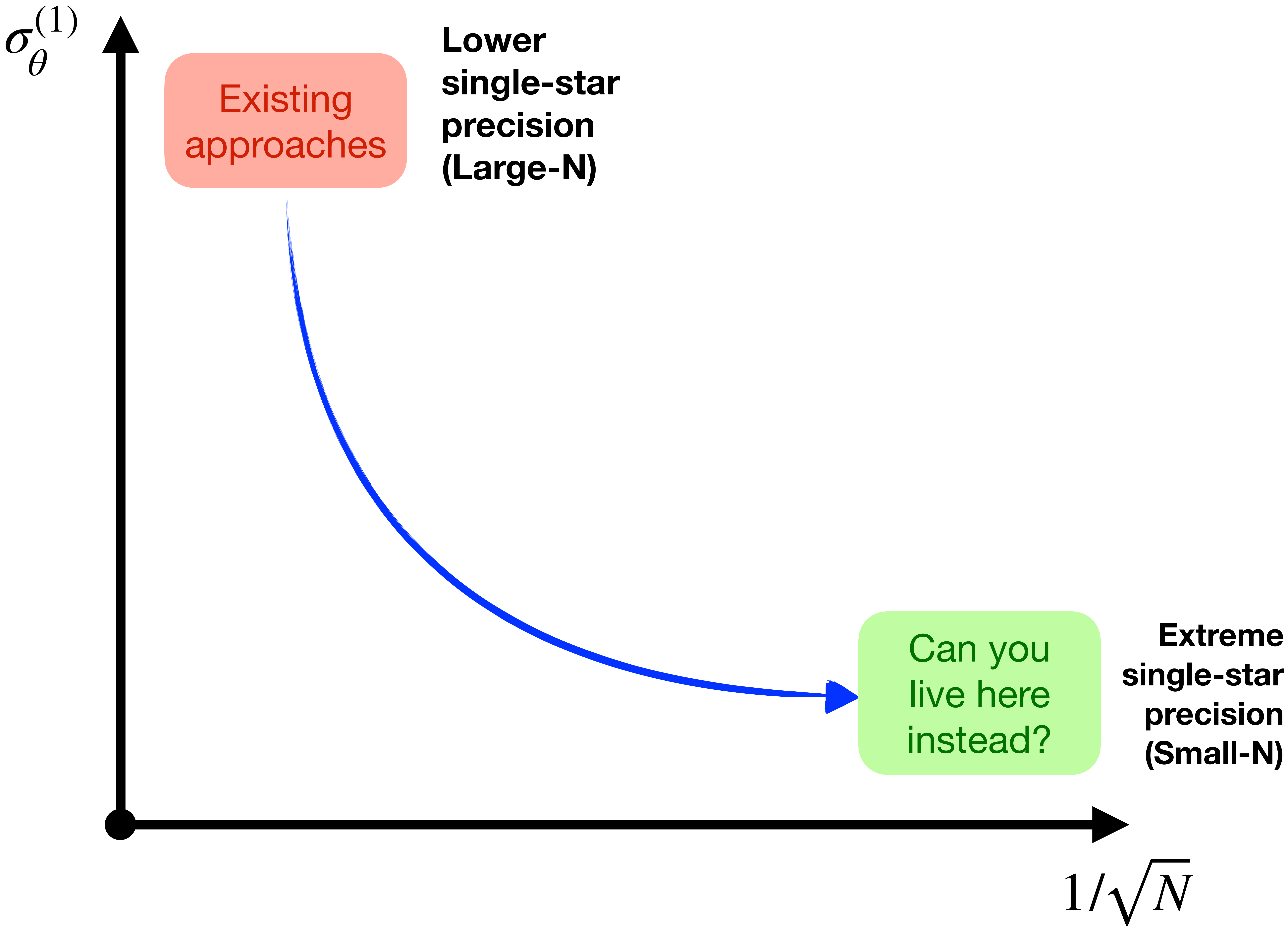

$\sigma_\theta^{(1)}$

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Can you live here instead?

Extreme single-star precision (Small-N)

$1/\sqrt{N}$

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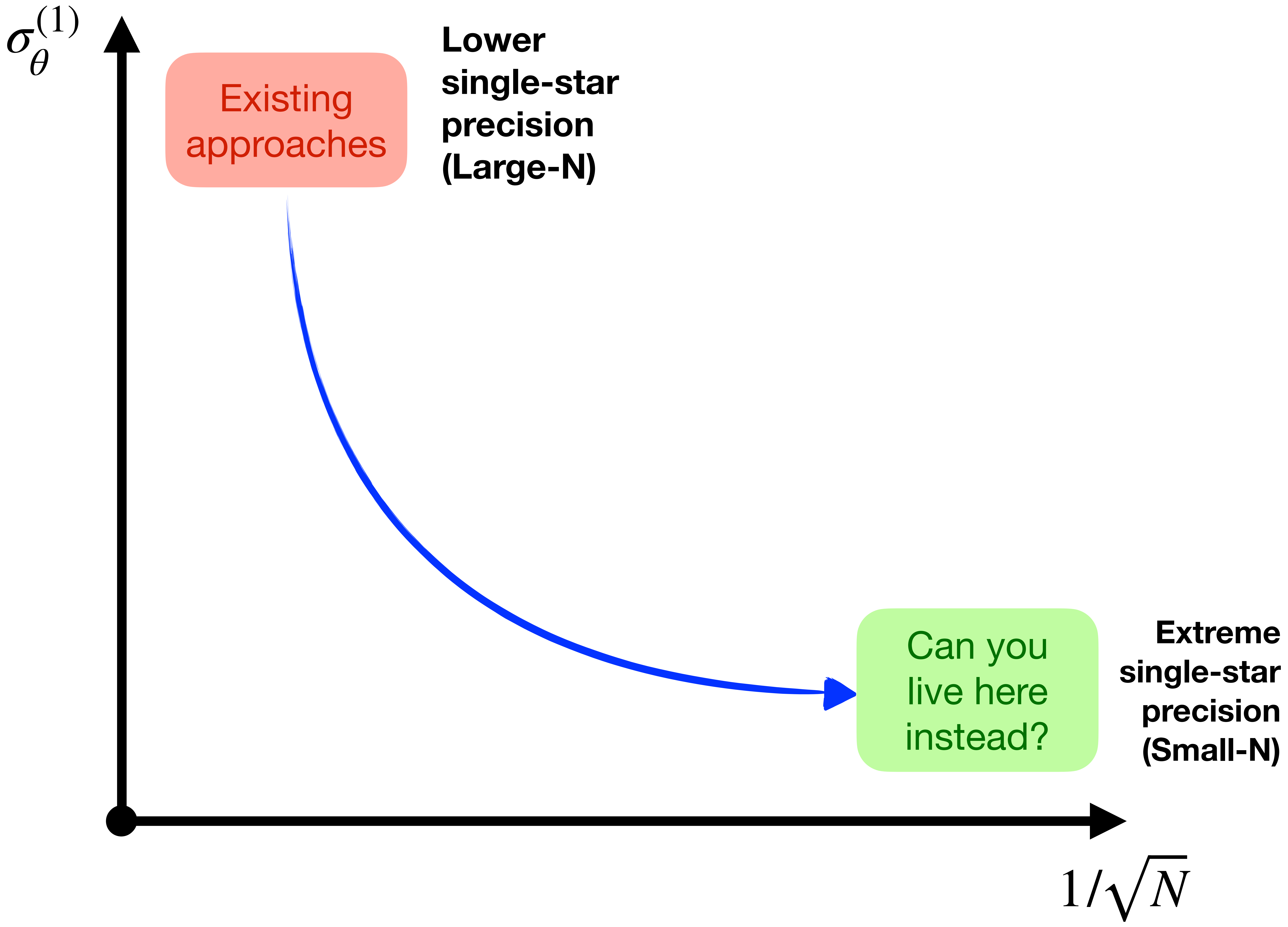

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We study this alternative optimisation

Two classes of issues

Are there sufficiently stable sources to measure?

How would you make the measurement?

Intrinsic source stability

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

*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.

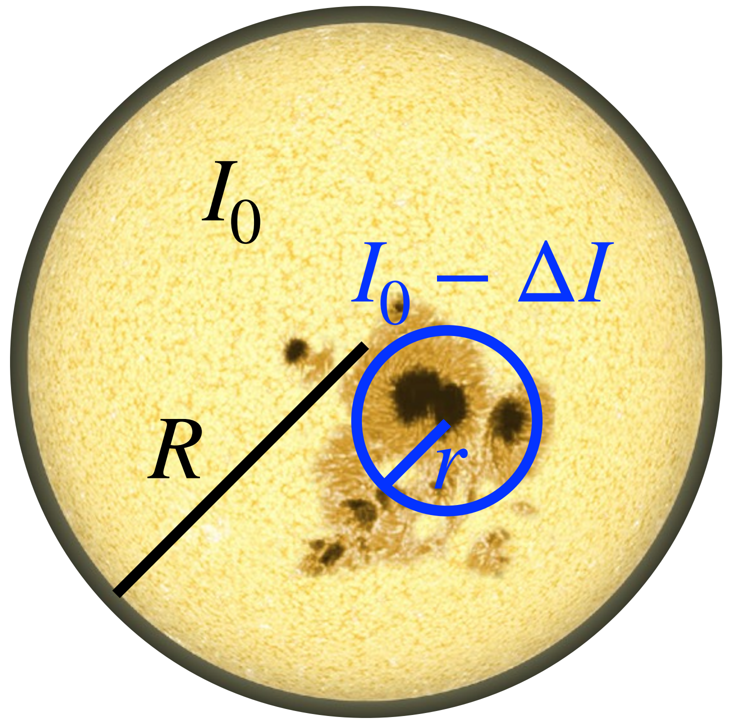
Starspots on WD

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

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.*

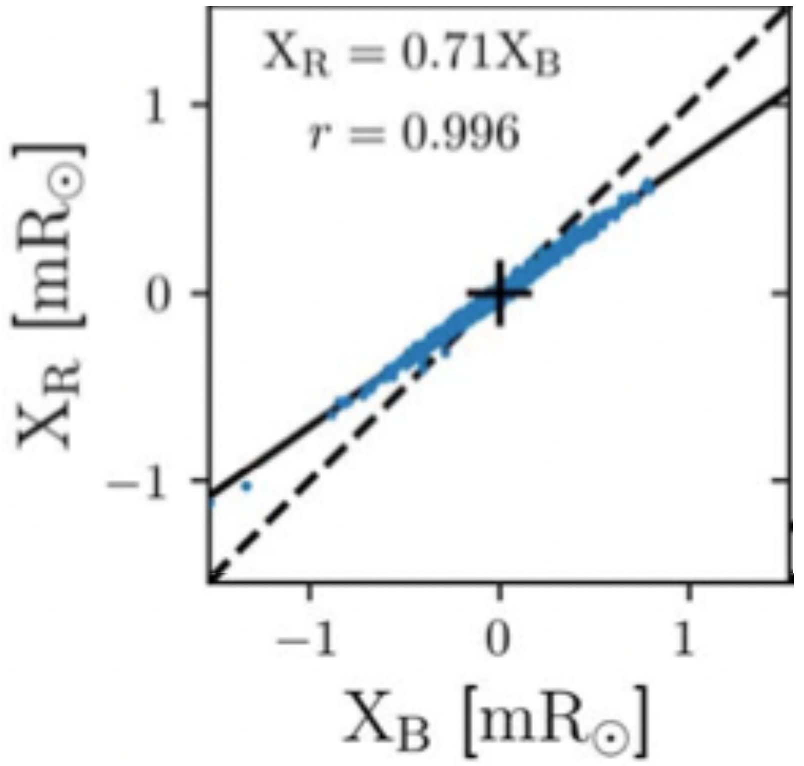
*excluding tuned geometries where the star is viewed almost directly down the rotational axis and the spot is close to the pole

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 diameter $d_{\text{body}} \gtrsim 2.5 \times 10^3\,\text{km}$ $\qquad (\rho_{\text{body}} \sim 3\,\text{g/cm}^3)$

Moon / dwarf planet sized object is a problem**.**

Intrinsically not many objects of this class in **any** stellar system (cf. our own: 4 such objects)

Frequency contamination is narrowband: stable orbits over $T_{\text{obs}} \sim 10\,\text{yrs}$ gives $\Delta f_{\text{blind}} \sim 1/T_{\text{obs}} \sim 3\,\text{nHz}$.

WD Planetary Systems

AGB phase preceding WD leads to star radius ~ AU. Clears inner few AU of the system. *Problem solved?*

Not so fast… dynamical age of planetary system is "reset" by the AGB mass-loss event.
Complicated/chaotic post-AGB system evolution can re-populate interior of the system with planets.

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

See our paper for an extensive list of references on these topics

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

Mitigation: Use accretion evidence as a veto criterion to try avoid such systems. **No guarantee that this omits all WD with planets!**

Back to previous argument: only a few such planets, and only narrow frequency bands blinded by individual planets around individual WD. $\mathcal{O}(\ll 1)$ fraction of frequency range blinded & different for different systems.

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Mitigation: Reflex motion also not exactly degenerate with a GW. Allows some discrimination? Needs modelling.

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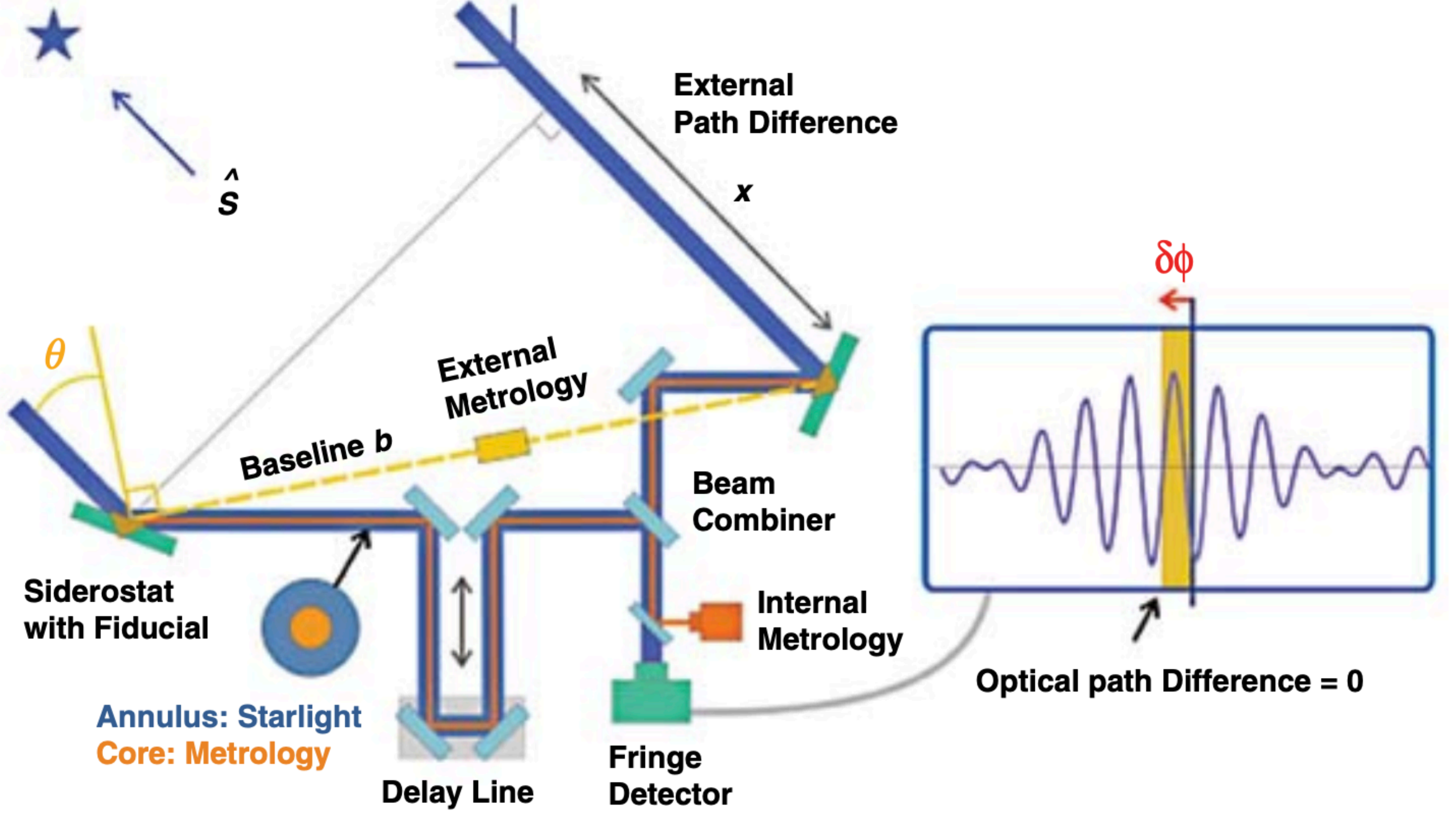
WDs STILL LOOK ATTRACTIVE AS A CLASS OF TARGETS!
…although some specific WD may be problematic

Stellar Interferometry

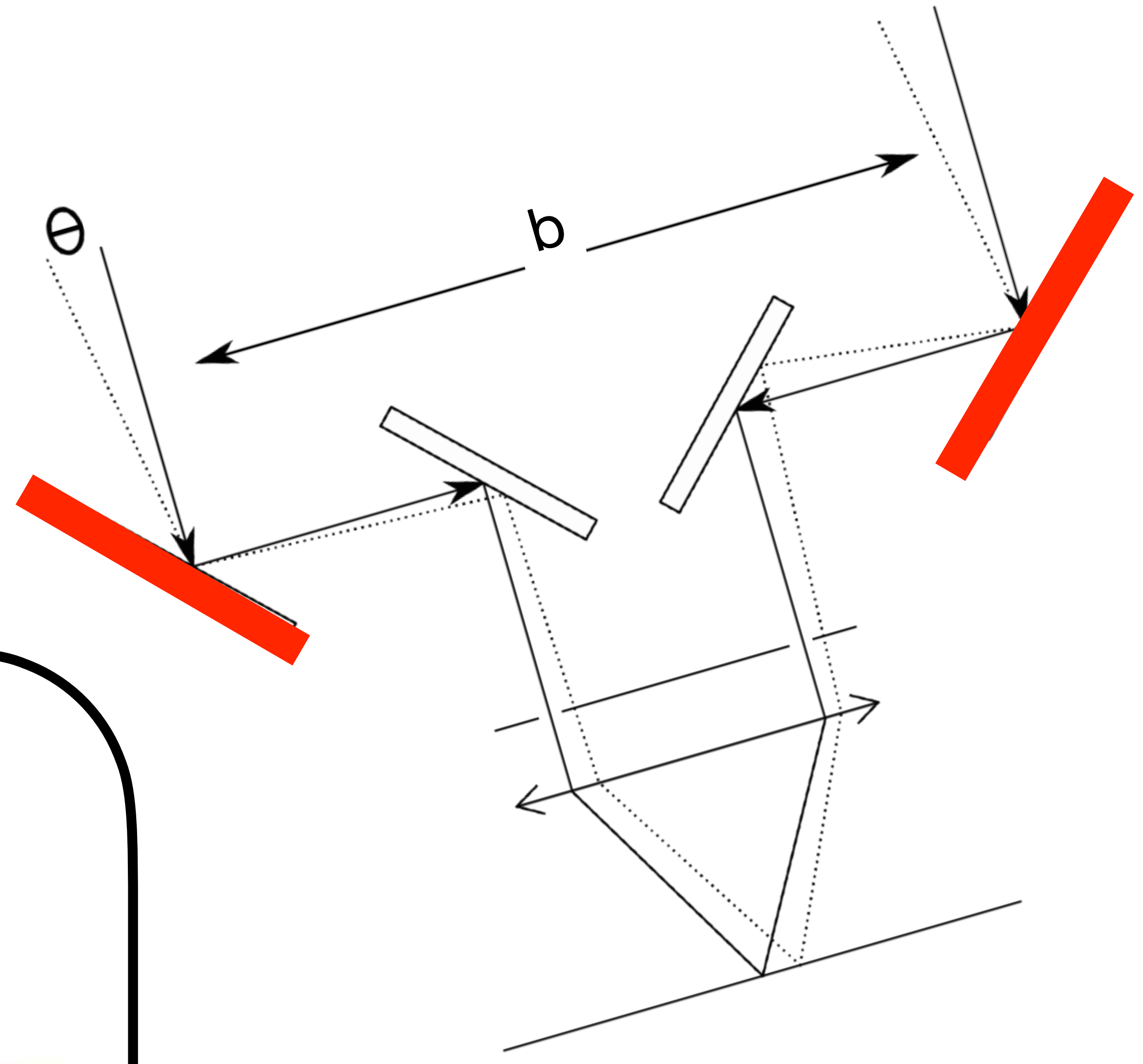
How do you measure an angular location to pico-arcsecond accuracy?

Space-based stellar interferometry with active baseline metrology.

Multiple separate, formation-flown spacecraft with individual light-collectors



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



Measure 3 things:

(1) white-light interference pattern — starlight

(2) internal optical path lengths
(internal metrology) — lasers

(3) actual baseline distance b
(external metrology) — lasers

Knowing (1) and (2) gives you

$$x = b \cdot \hat{s} = b \sin\theta$$

Knowing (3) 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)**.**

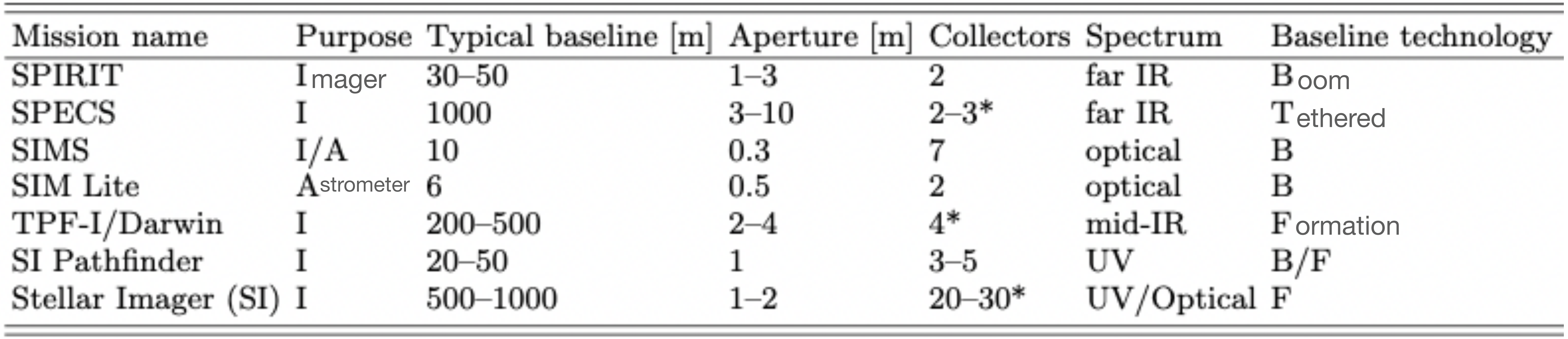
Separate, formation-flown collector spacecraft.

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.

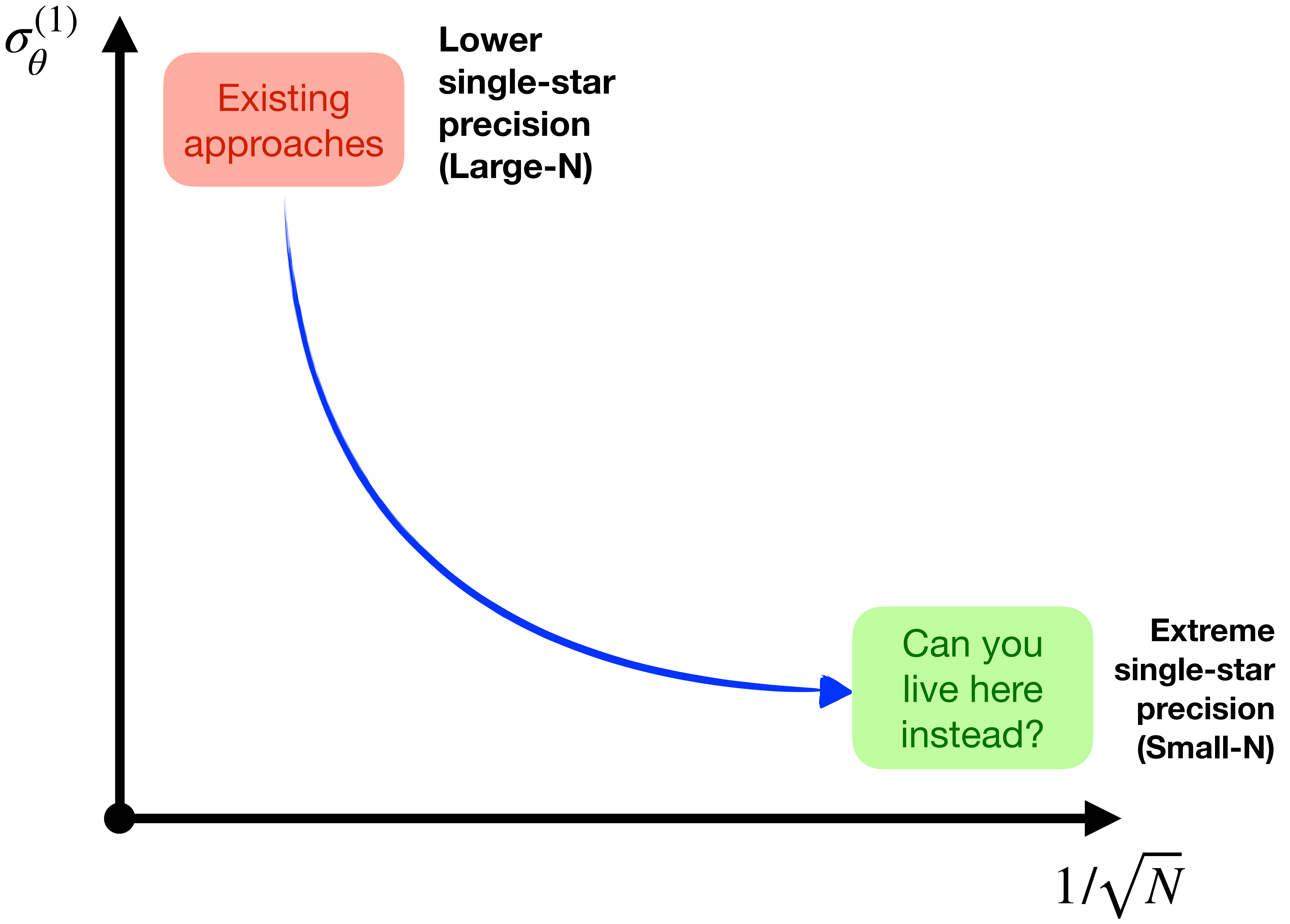
All-new, GW-science motivation for space-based instruments of this type!

Additional requirements:

- 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

Summary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Can you live here instead?
Extreme single-star precision (Small-N)
$1/\sqrt{N}$

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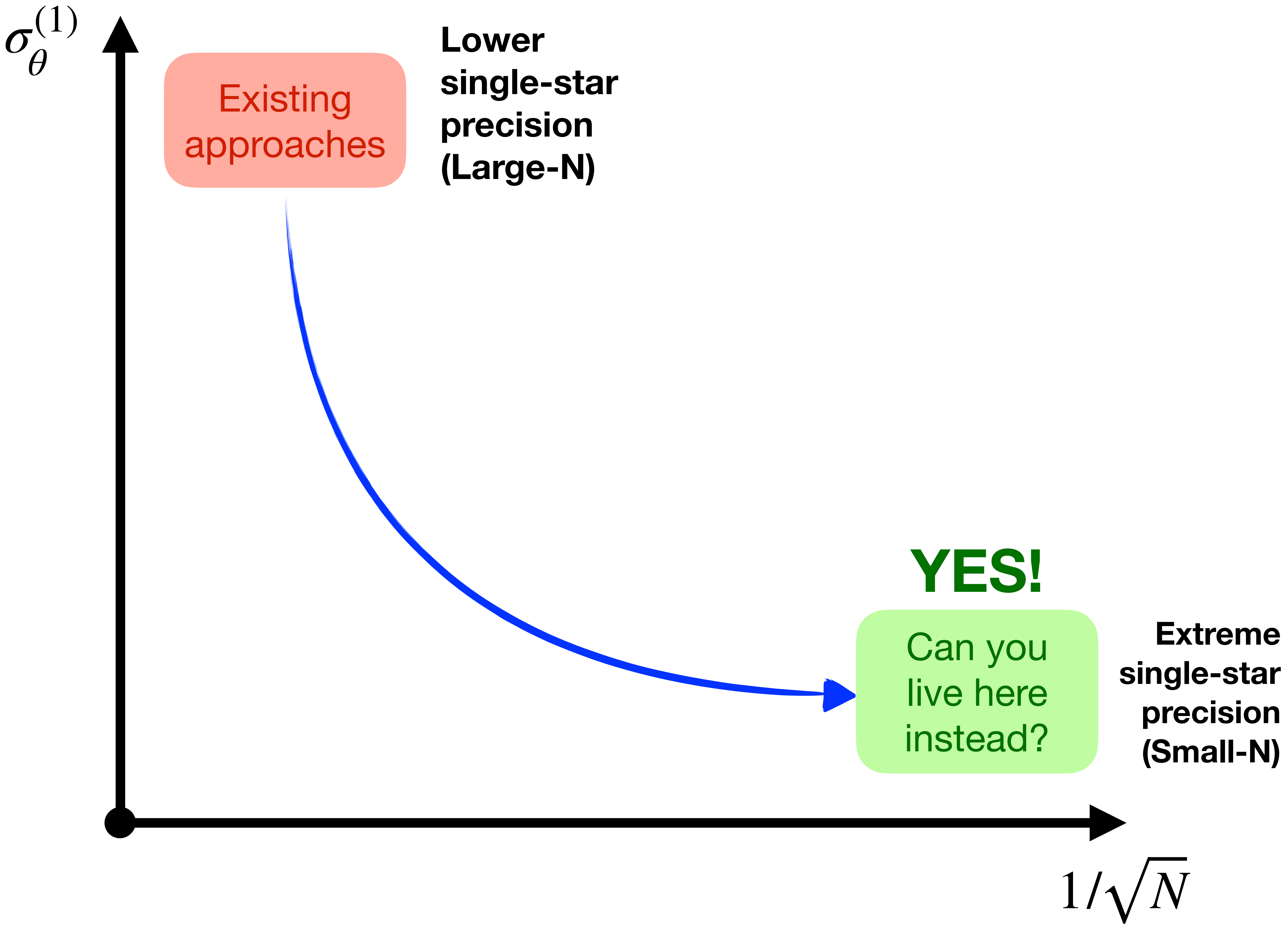

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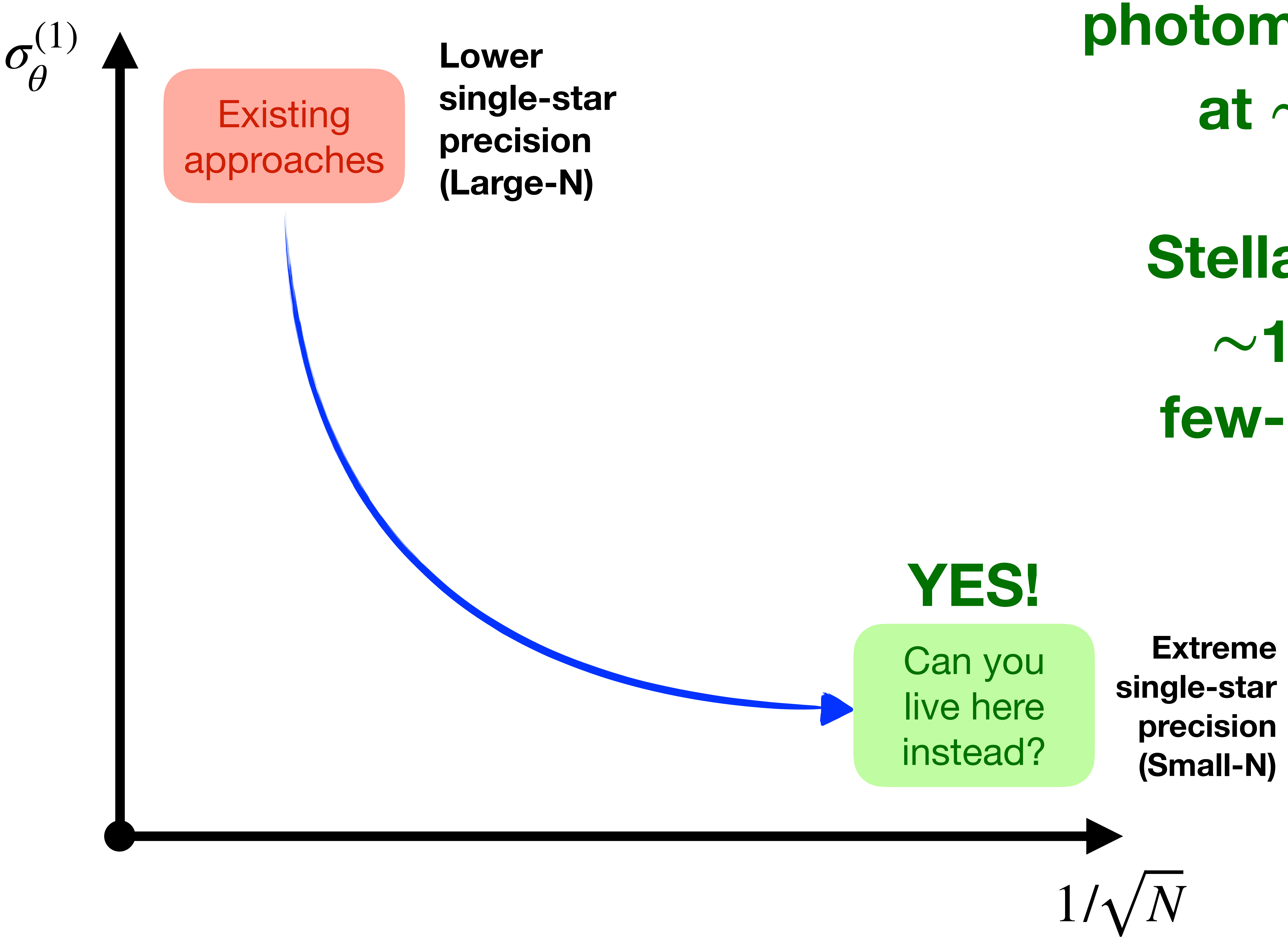

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Hot, non-magnetic, photometrically stable WD at ∼kpc distances

Stellar interferometry:
∼100km baseline
few-meter collectors

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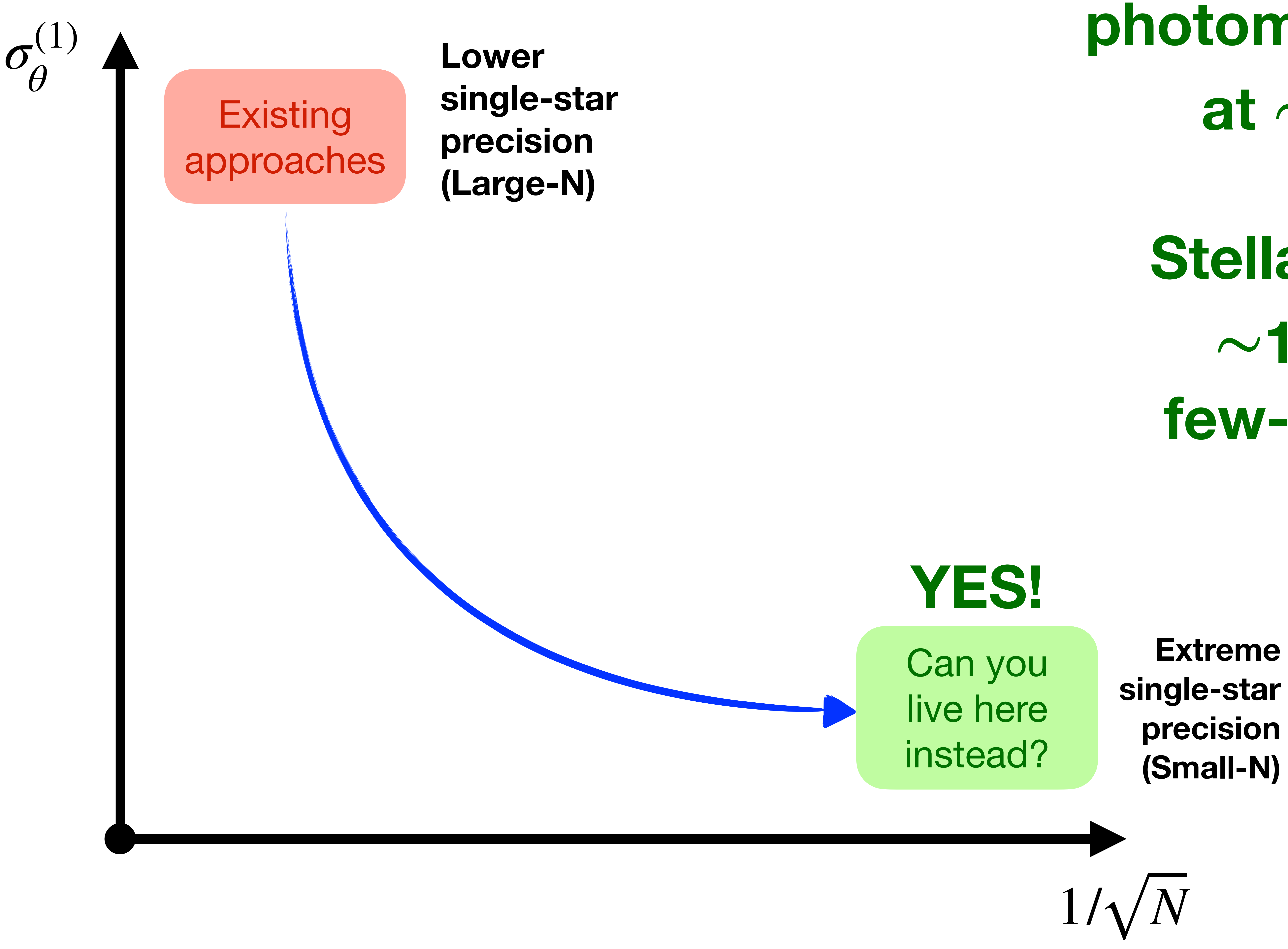

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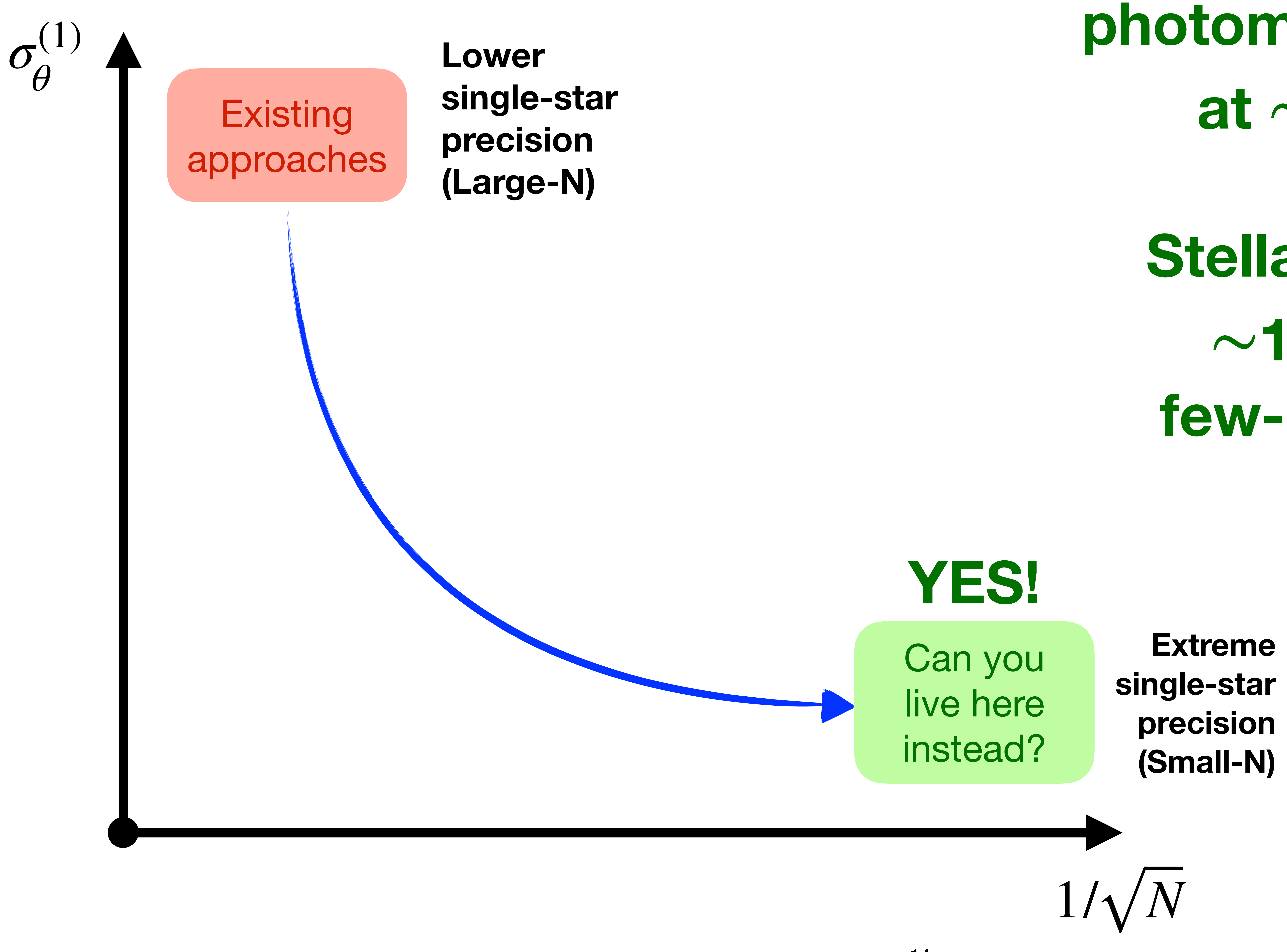

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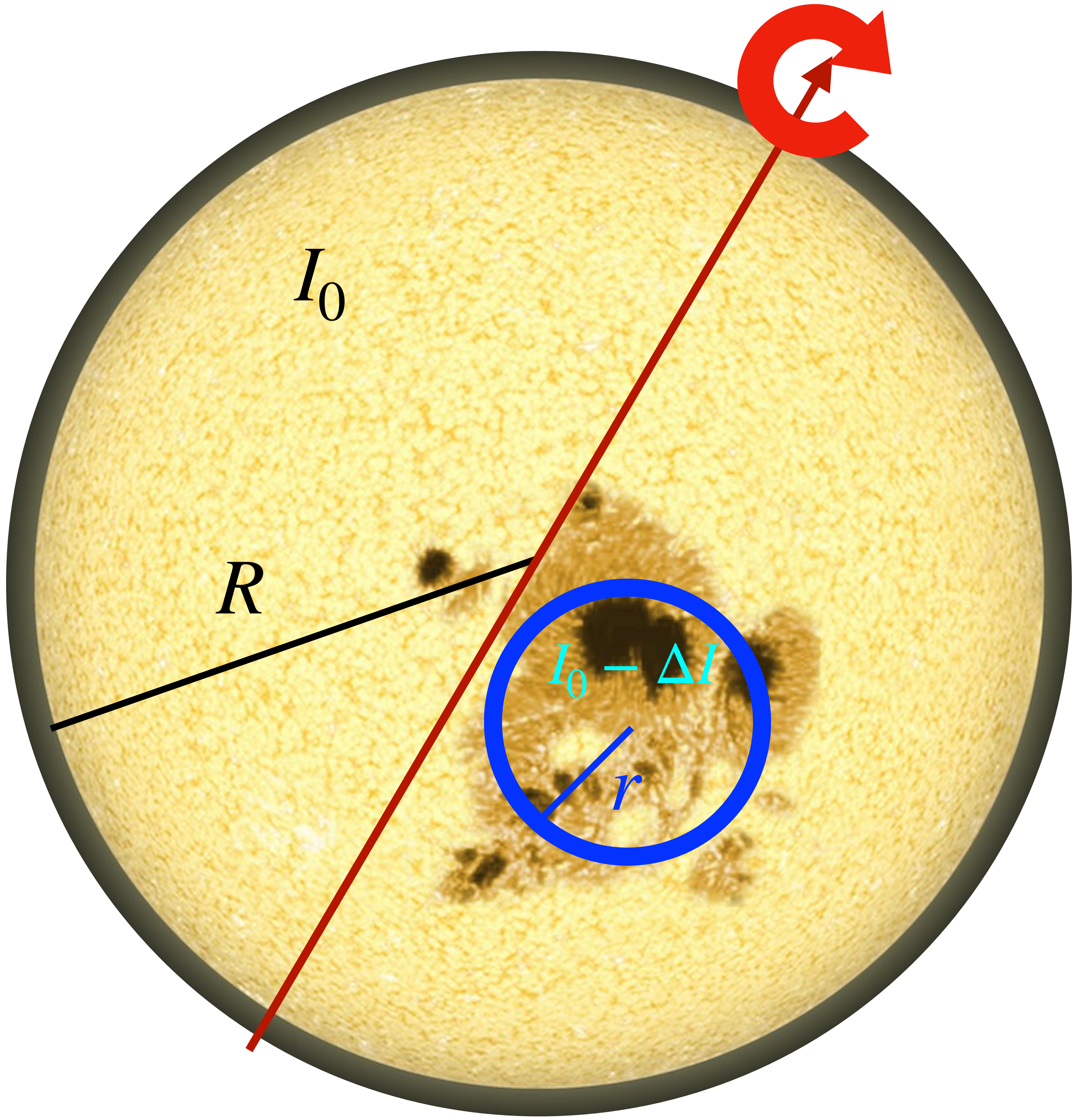
BACKUP

Starspots



Shift in the photometric center:

$$\Delta x \sim \frac{\Delta I}{I_0} \times \frac{r^2}{R}$$

Apparent angular shift of the photometric center:

$$\Delta\theta \sim \frac{\Delta I}{I_0} \times \frac{r^2}{Rd} \sim \frac{\Delta L}{L_0} \times \frac{R}{d}$$

Fixing fractional luminosity change $\Delta L / L_0$:
smaller, more distant = smaller angular shift.

Modulates at rotational period; averaged out up to an offset.

Spot(s) configuration ***changes*** stochastically by $\mathcal{O}(1)$ over ~10 day. So the offset changes. This is a noise source.