Title: Two-Photon Methods for Astrometric Gravitational Wave Detection

Speakers: Paul Stankus

Collection/Series: Future Prospects of Intensity Interferometry

Subject: Cosmology

Date: November 01, 2024 - 11:35 AM

URL: https://pirsa.org/24110041

Abstract:

With the observation of gravitational waves (GW's) at high, kilohertz frequencies by LIGO and the evidence for GW's at low, nanohertz frequencies from NANOGrav there is a new emphasis on exploring the GW landscape at intermediate frequency ranges. Beyond the two measurement methods used in these observations, i.e. laser metrology in LIGO and pulsar timing offsets in NANOGrav, we have been developing a third approach of observing astrometric GW signatures, which is very well suited to the intermediate microhertz frequency range. While astrometric GW observations have been discussed in the context of survey missions, e.g. GAIA, this presentation will exhibit a potentially superior approach using long baseline two-photon interferometry, with both space-based and ground-based platforms. The practicalities of a near-future experiment will be particularly highlighted

Two-Photon Methods for Astrometric Gravitational Wave Detection

(and more!)

Brookhaven National Laboratory

$\langle BNL|\hat{a}^{\dagger}|QIST\rangle$

Paul Stankus, BNL

Future Prospects for Intensity Interferometry

Perimeter Institute, 1 November 2024

Overall

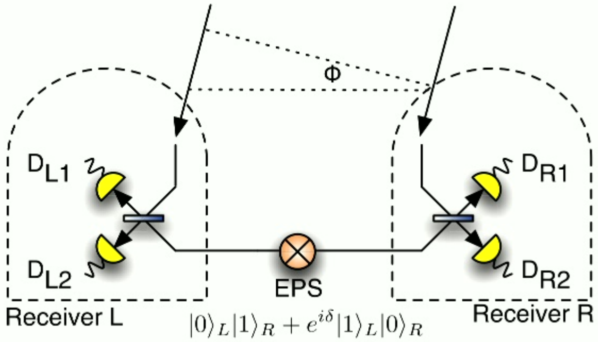
- Beyond imaging, think about astrometry
- Intensity interferometry can do precision (μarcsec) astrometry on bright objects
- Many applications: my favorite is gravitational wave detection

Agenda

- New two-photon interferometry for precision astrometry
  - In association with R. Abrahao, J. Crawford, A. Nomerotski, A. Slozar, S. Vintskevitch, J. Haupt, B. Farella, A. Mueninghoff, Z. Chen, M. Keach, S. Bellavia, J. Crawford, J. Martinez, et.al.

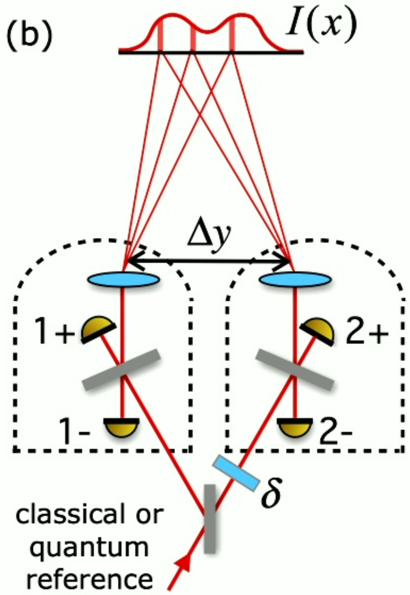
- New gravitational waves with astrometry via interferometry
  - In association with Surjeet Rajendran, Peter Graham, Bruce Macintosh, Sven Hermann, Michael Fedderke

Quantum-Enhancing Michelson?



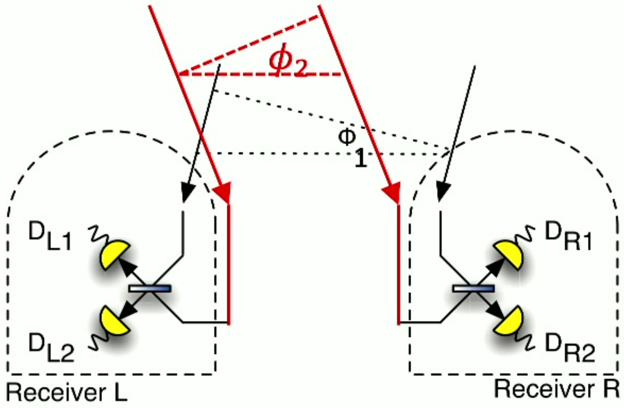
Gottesman, et.al. PRL 2012

Enabling longer baselines by supplying path-entangled ground photon over quantum network



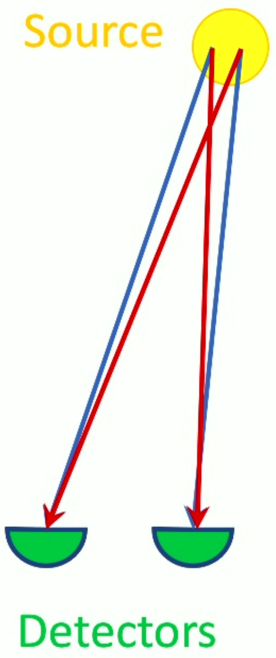
Brown, et.al. PRL 2023

First GJC bench demonstration

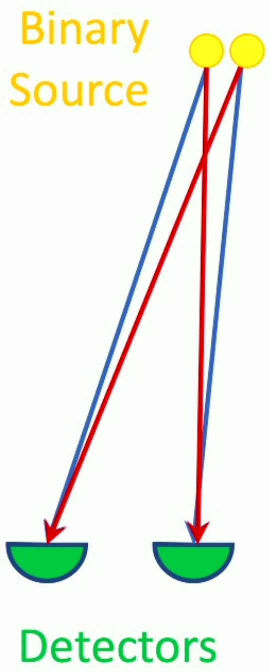


Our idea: what if we replace the "ground" path-entangled photon with another photon from the sky?

HBT for astrometry of binaries



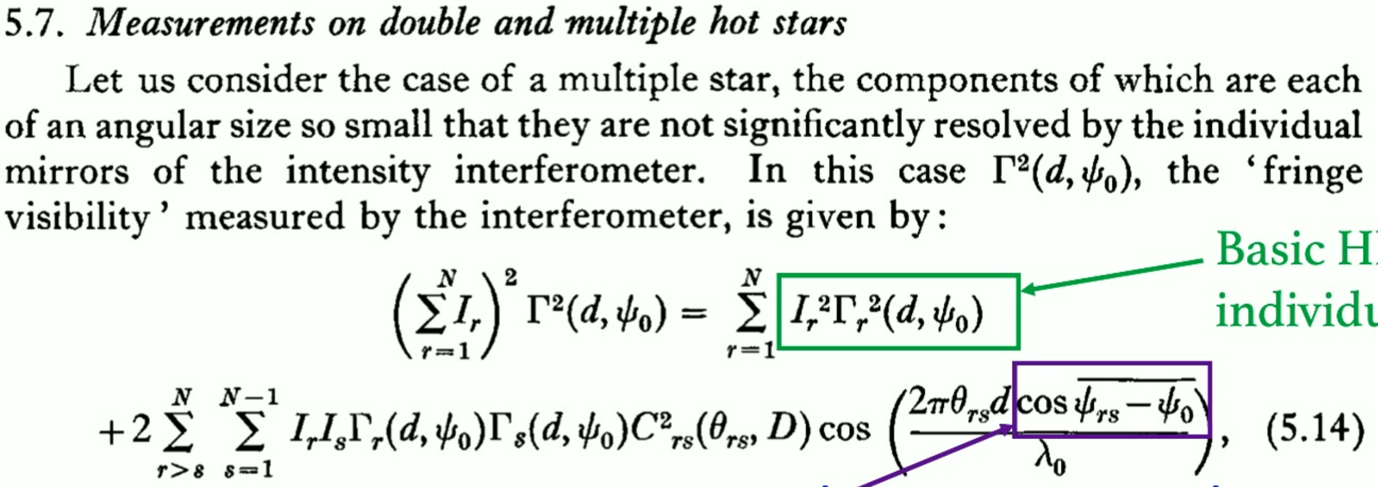
Standard HBT intensity interferometry; depends on source having *thermal* photon statistics.



HBT on binary source yields fringes with baseline and opening angle – astrometry. Does *not* depend on source being thermal.

HBT for astrometry of binaries

R.Q. Twiss (1969) Applications of Intensity Interferometry in Physics and Astronomy, Optica Acta: International Journal of Optics, 16:4, 423-451, DOI: 10.1080/71381819



5.7. *Measurements on double and multiple hot stars*

Let us consider the case of a multiple star, the components of which are each of an angular size so small that they are not significantly resolved by the individual mirrors of the intensity interferometer. In this case $\Gamma^2(d,\psi_0)$, the 'fringe visibility' measured by the interferometer, is given by:

$$\left(\sum_{r=1}^{N} I_r\right)^2 \Gamma^2(d,\psi_0) = \sum_{r=1}^{N} \boxed{I_r{}^2\Gamma_r{}^2(d,\psi_0)}$$

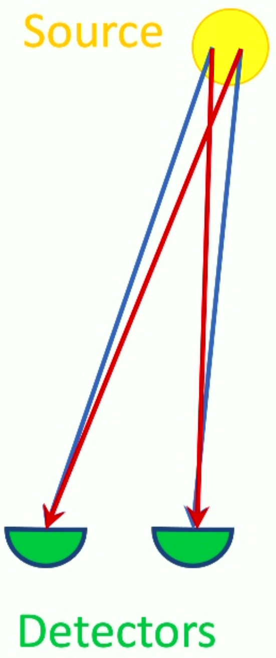
$$+2\sum_{r>s}^{N}\sum_{s=1}^{N-1} I_rI_s\Gamma_r(d,\psi_0)\Gamma_s(d,\psi_0)C^2{}_{rs}(\theta_{rs},D)\cos\left(\frac{2\pi\theta_{rs}d\,\boxed{\cos\overline{\psi_{rs}-\psi_0}}}{\lambda_0}\right), \qquad (5.14)$$

Basic HBT enhancement for individual thermal sources

Earth baseline rotation

Pair rate *oscillation* does *not* depend on sources being thermal!

Our HBT Generalization ("SNSV")



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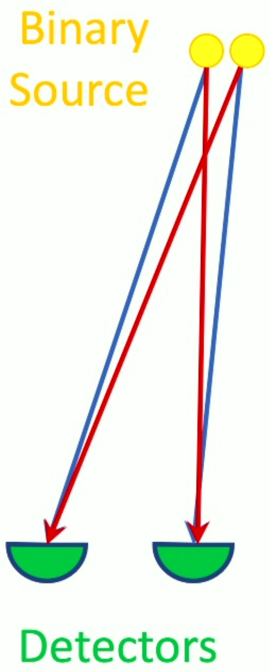
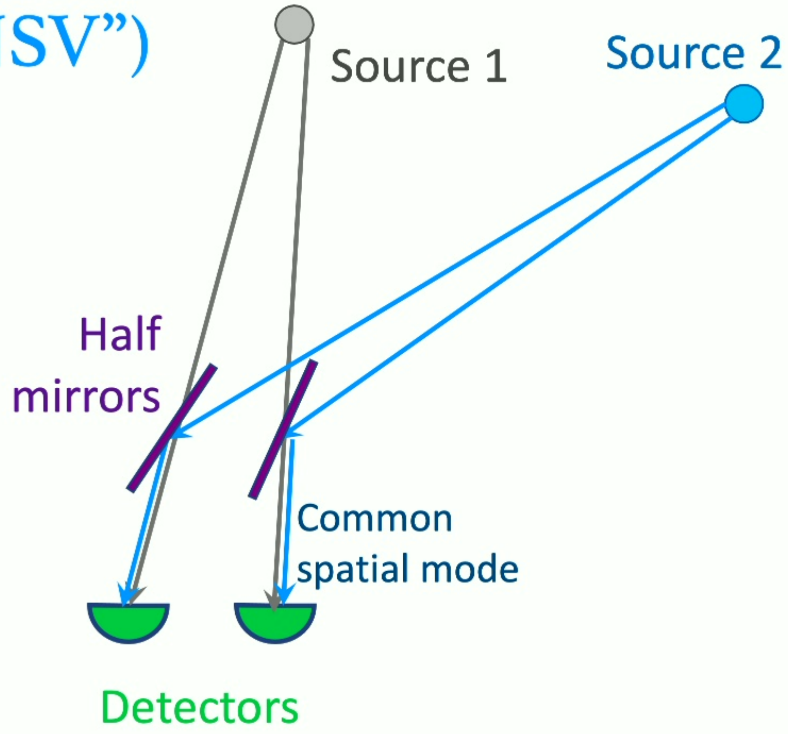
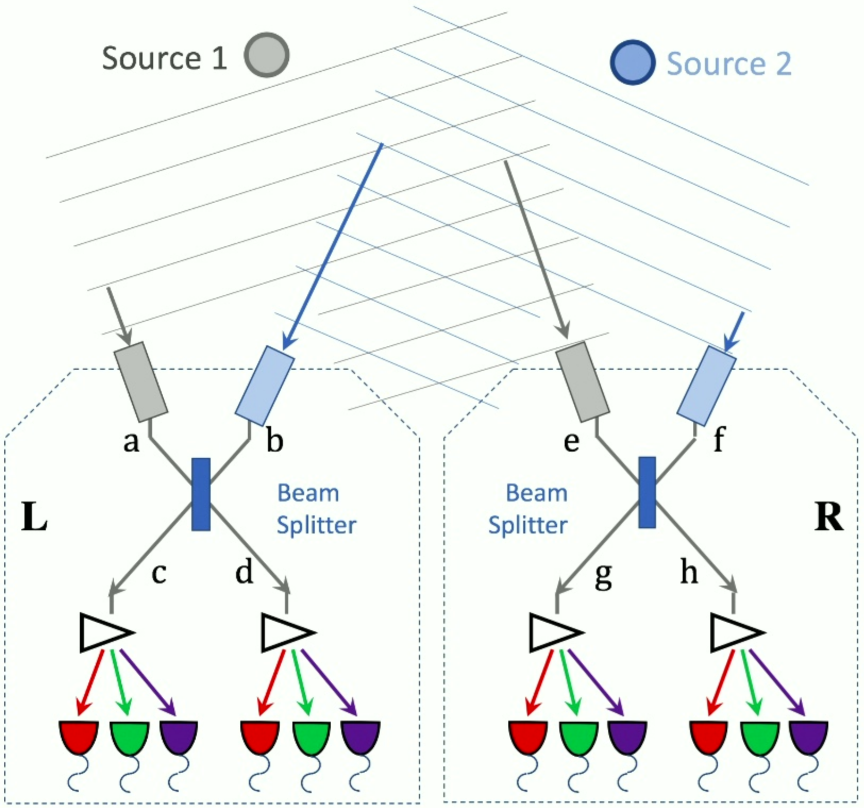


HBT on binary source yields fringes with baseline and opening angle – astrometry. Does *not* depend on source being thermal.



Natural extension for wide-angle astrometry is to bring widely separated sources into common spatial mode: two photon amplitude interferometry for precision astrometry



Allows long-baseline precision measurement with *no optical connection* between stations

Instrumentation and Methods for Astrophysics

Vol. 5, 2022 • November 01, 2022 IST

Two-photon amplitude interferometry for precision astrometry

Paul Stankus , Andrei Nomerotski , Anže Slosar , Stephen Vintskevich

https://doi.org/10.21105/astro.2010.09100

Base combinatoric pair rate

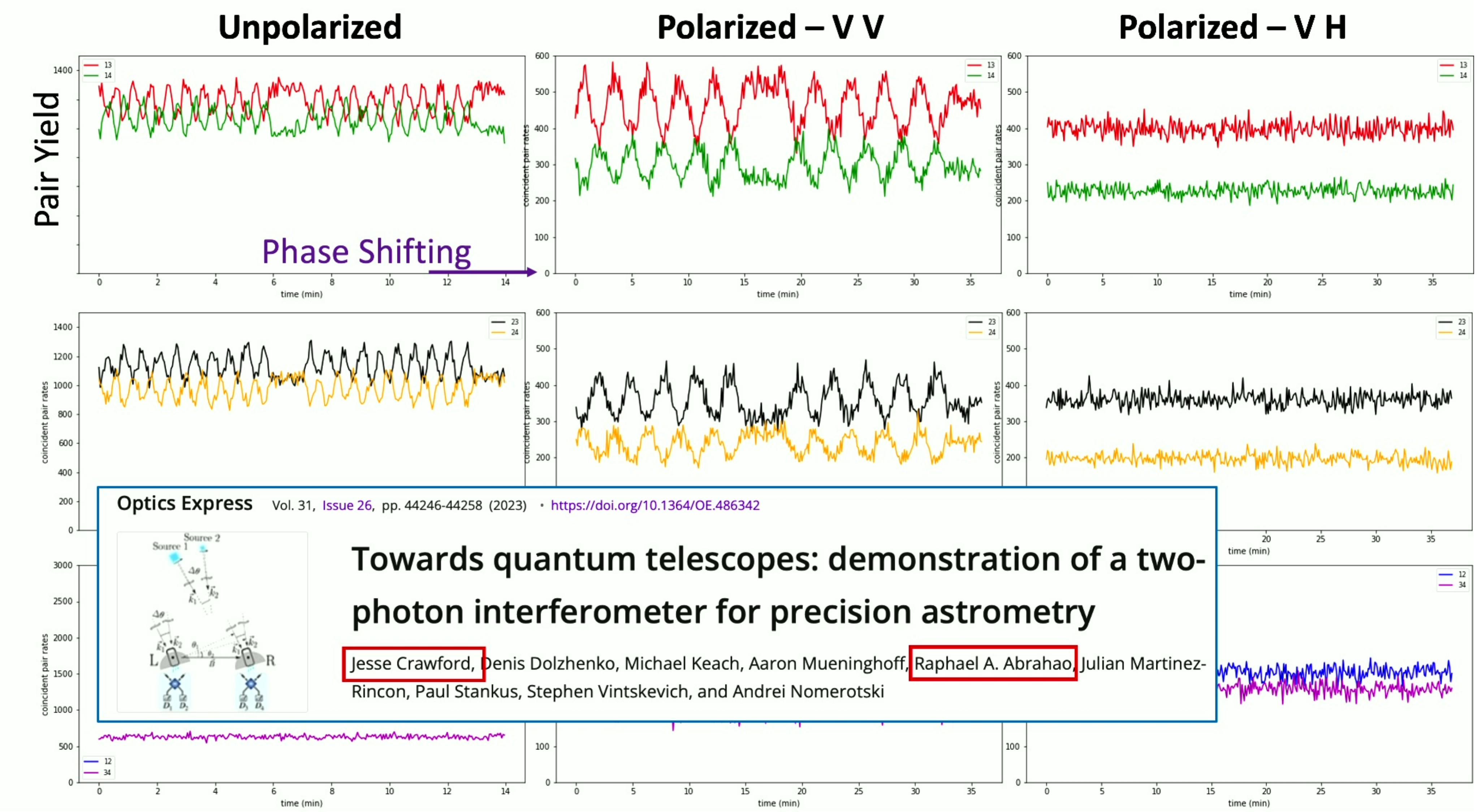
HBT enhancement

$$N_c(xy) = \eta_1\eta_2 A^2 \int_0^{T_r} P^{\text{two photons}}_{L,R,\tau}\, d\tau =$$

$$A^2\eta_1\eta_2 T_r \Bigg[\boxed{(I_1+I_2)^2} + \boxed{I_1^2\frac{\tau_c g_{11}}{T_r} + I_2^2\frac{\tau_c g_{22}}{T_r}} \pm \boxed{2I_1I_2\frac{\tau_c g_{12}}{T_r}\cos\left(\frac{\omega_0 B\boxed{(\sin\theta_1-\sin\theta_2)}}{c}+\frac{\omega_0\Delta L}{c}\right)} \Bigg]$$

Oscillatory term, fringe passing

Opening angle => astrometry!



Phase Shifting

Optics Express Vol. 31, Issue 26, pp. 44246-44258 (2023) • https://doi.org/10.1364/OE.486342

Towards quantum telescopes: demonstration of a two-photon interferometer for precision astrometry

Jesse Crawford, Denis Dolzhenko, Michael Keach, Aaron Mueninghoff, Raphael A. Abrahao, Julian Martinez-Rincon, Paul Stankus, Stephen Vintskevich, and Andrei Nomerotski

World-competitive precision

Instrumentation and Methods for Astrophysics

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Paul Stankus , Andrei Nomerotski , Anže Slosar , Stephen Vintskevich

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$$\sigma\left[\Delta\theta\right] = \sqrt{\frac{6}{\pi^2\kappa}}\,\frac{1}{V}\,\frac{\lambda}{B}\,\frac{1}{T\Omega_{\oplus}\,\sin\theta_0}\,\frac{1}{\sqrt{\bar{n}T}}$$

$\overline{n}$ = average pair rate

T = total observation time

A modest experiment:

- Bright stars, mag 2
- 1 m^2 collecting area
- 10^4 seconds observation
- 0.15 nsec time resolution
- 10^4 spectral channels

Idea: Dynamic Astrometry

Track day-over-day changes in $\Delta\theta$ to observe parallax, proper motion, orbital motion, gravitational lensing

$$\sigma[\Delta\theta] \sim 10\mu\text{as} \ (\sim 10^{-11}\ \text{rad})$$

1 mas HIPPARCOS (1989-1993)

8-20 μas GAIA (2013-)

The many glories of μarcsec astrometry

- Improved parallax
  - Extra-galactic?
- Inverse parallax on spectroscopic binaries
  - Systematic check on distance ladder
- Wide binaries (don't say "MOND")
- Dark matter in the galaxy
  - "Halometry from Astrometry" (KvT et.al); Ultralight DM density waves
  - Gravitational lensing of gravitational waves, frequency artifacts (M. Caliskan)
- Stellar reflex motion from exoplanets
- Astrometric signature of low-frequency μHz gravitational waves

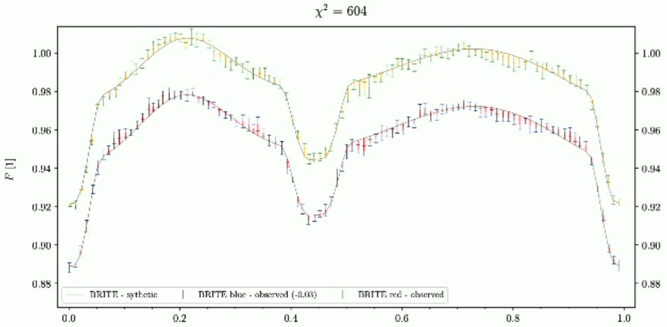
New!

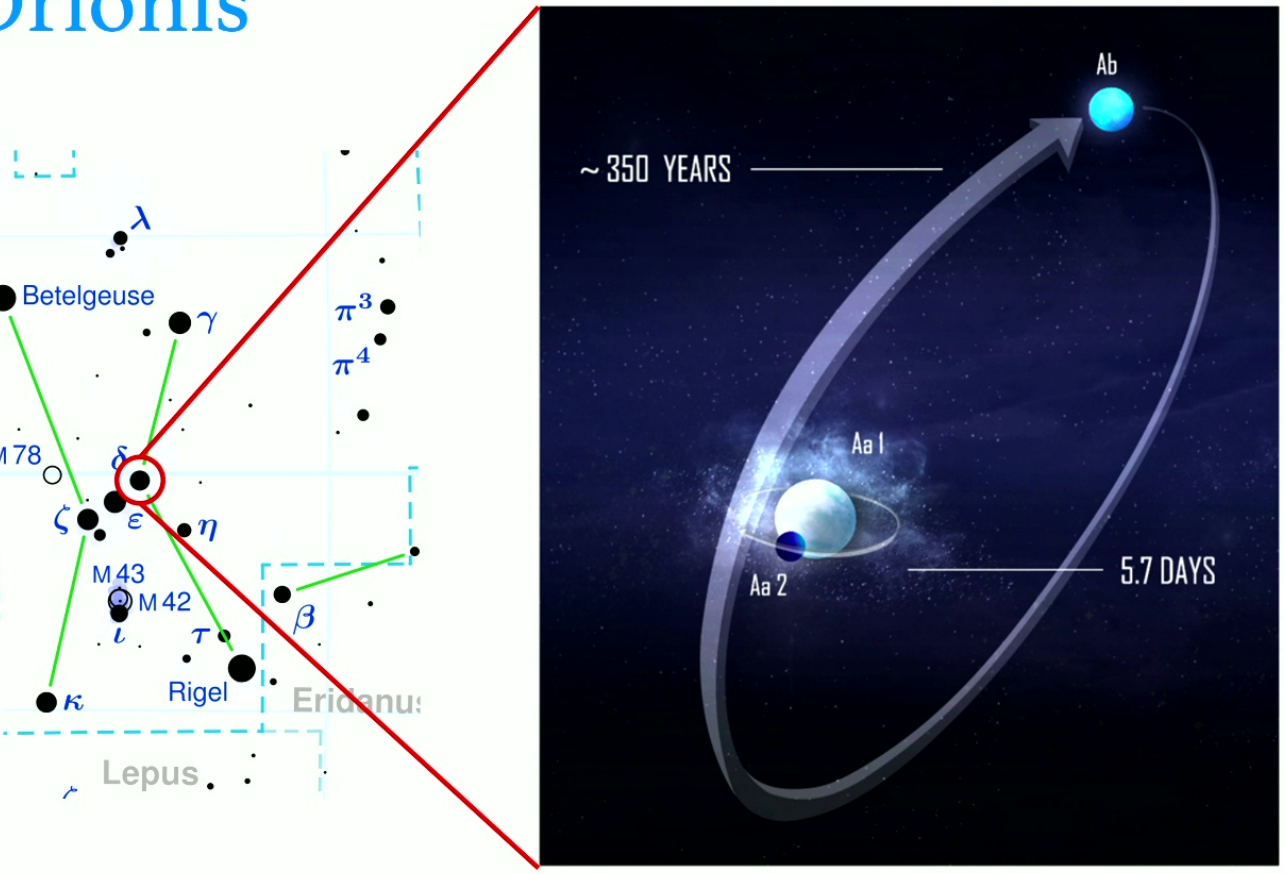
Candidate: δ Orionis

Very bright eclipsing binary

GAIA and HIPPARCOS parallaxes disagree – candidate for inverse parallax distance measurement?

Opluštilová, A., et al.: A&A 672, A31 (2023)



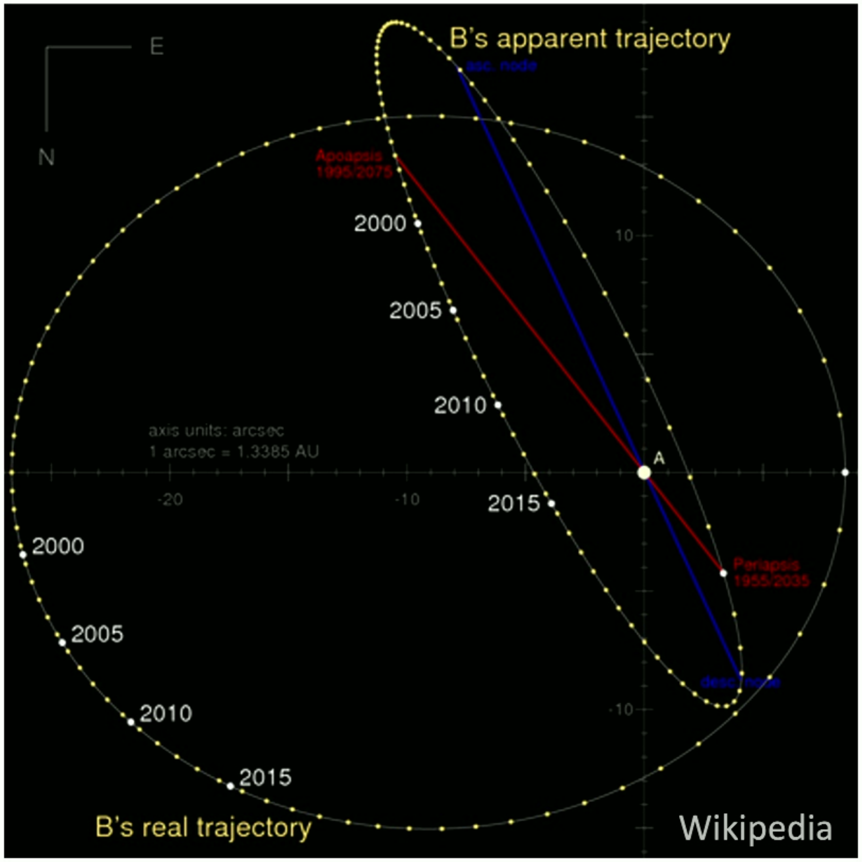


The Astrophysical Journal, 809:135 (20pp), 2015 August 20

A COORDINATED X-RAY AND OPTICAL CAMPAIGN OF THE NEAREST MASSIVE ECLIPSING BINARY, δ ORIONIS Aa. IV. A MULTIWAVELENGTH, NON-LTE SPECTROSCOPIC ANALYSIS

T. Shenar[1], L. Oskinova[1], W.-R. Hamann[1], M. F. Corcoran[2,3], A. F. J. Moffat[4], H. Pablo[4], N. D. Richardson[4], W. L. Waldron[5], D. P. Huenemoerder[6], J. Maíz Apellániz[7], J. S. Nichols[8], H. Todt[1], Y. Nazé[9,13], J. L. Hoffman[10], A. M. T. Pollock[11], and I. Negueruela[12]

Candidate: α Centauri A (+?)



Wikipedia

Astrometric stellar reflex motion from exoplanets works best on close systems

Alpha Centauri A-B binary, nearby and very bright (combined m_V~-0.25)

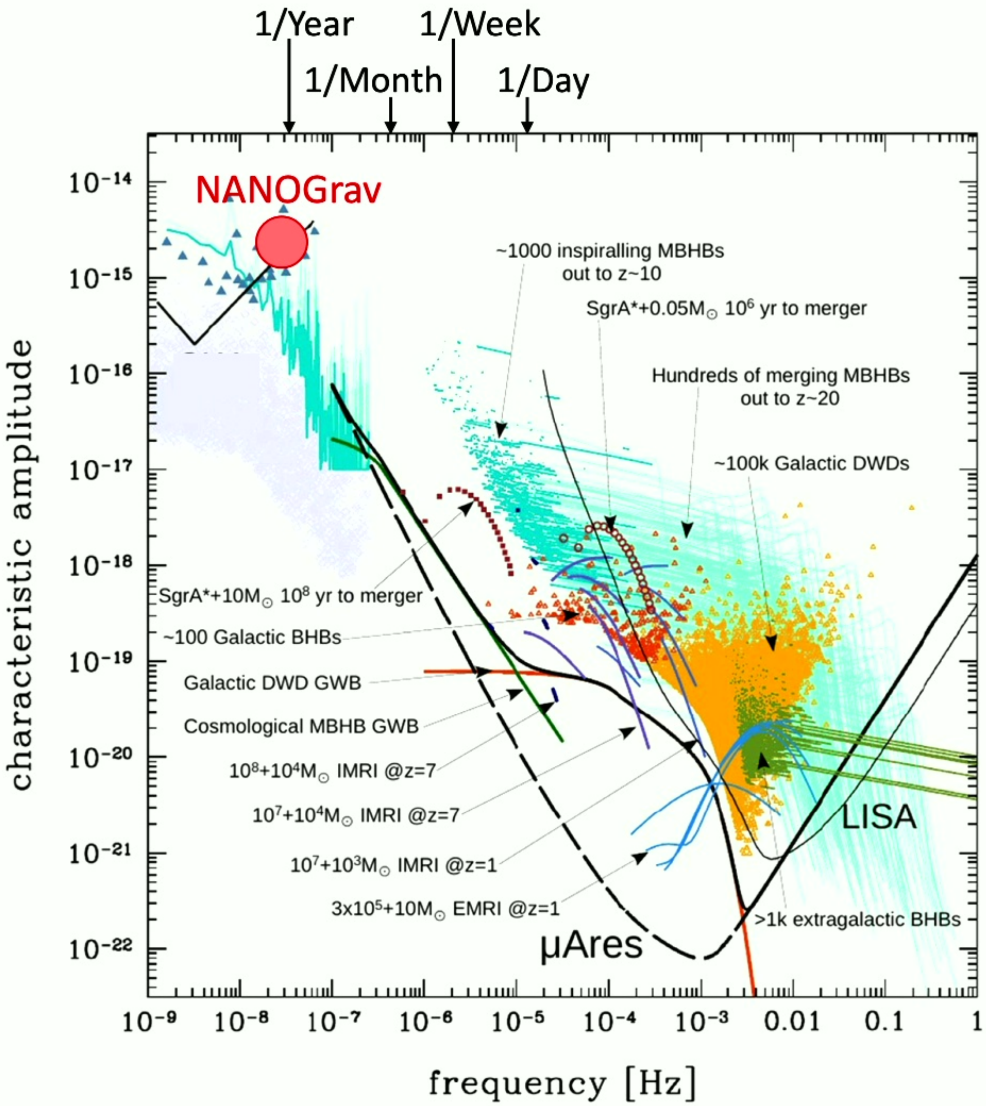
Is there a rocky planet around A?
B provides very convenient reference, within an isoplanatic patch (or close to it)

Would need μarcsec resolution observed over a few years

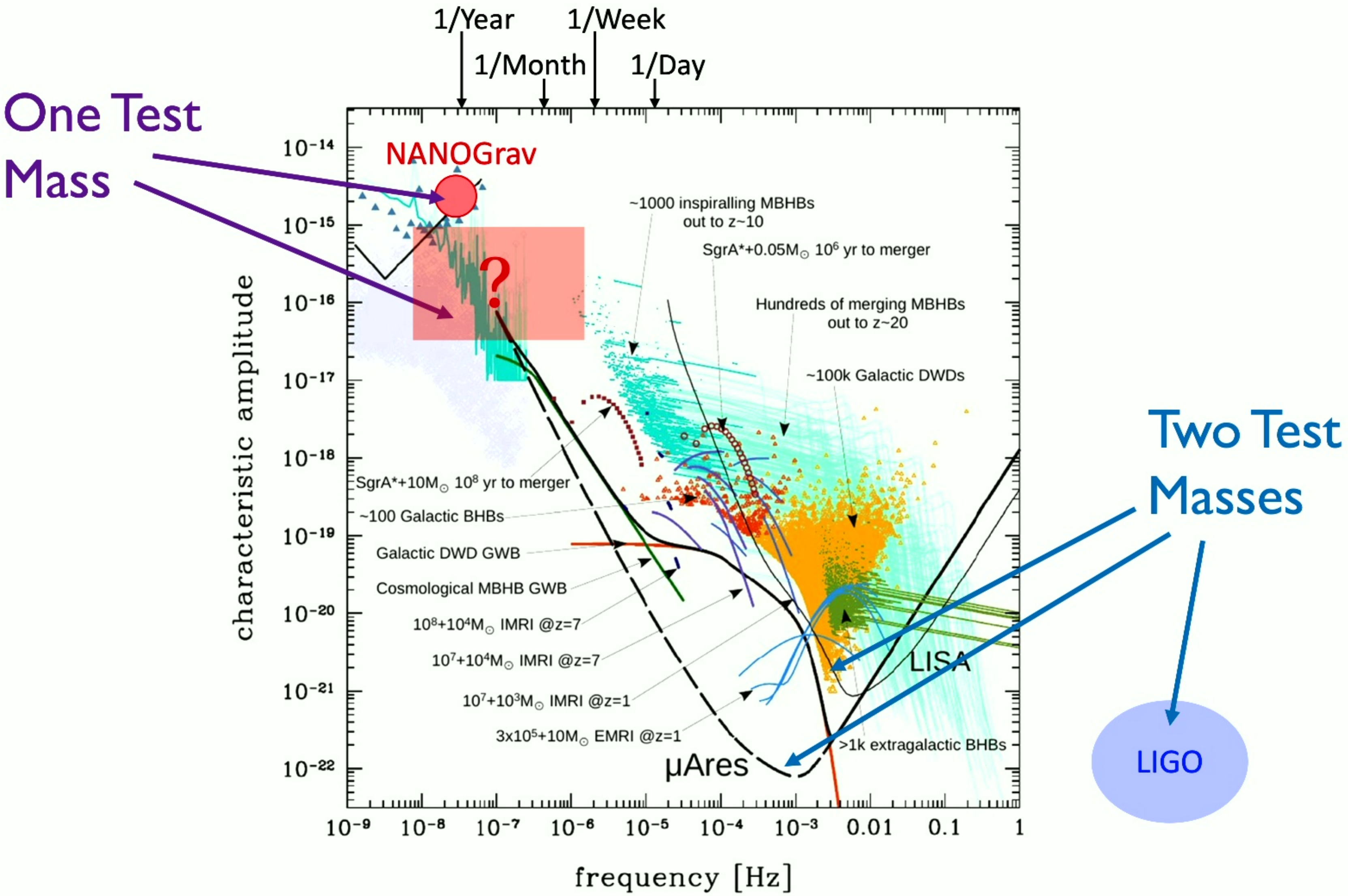
New Gravitational Waves at Low (~μHz) Frequencies using Interferometry

Grabbing hold of a very big fish

Gravitational Wave Landscape



LIGO



One Test Mass

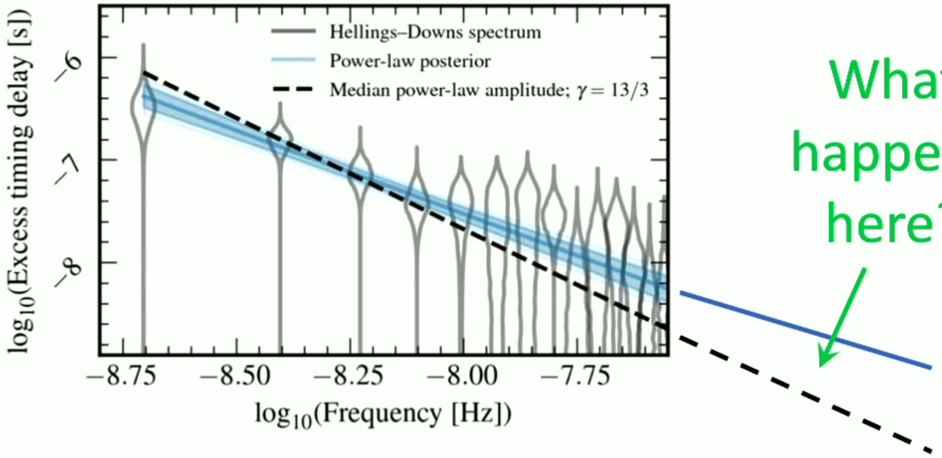
Two Test Masses

LIGO

Physics Agenda for GW in μHz range

Not at all inclusive, just a taste

Bread & Butter



What happens here?

Opportunistic

Loud sirens, SMBHB inspiral

Transients, mergers and periastron passage

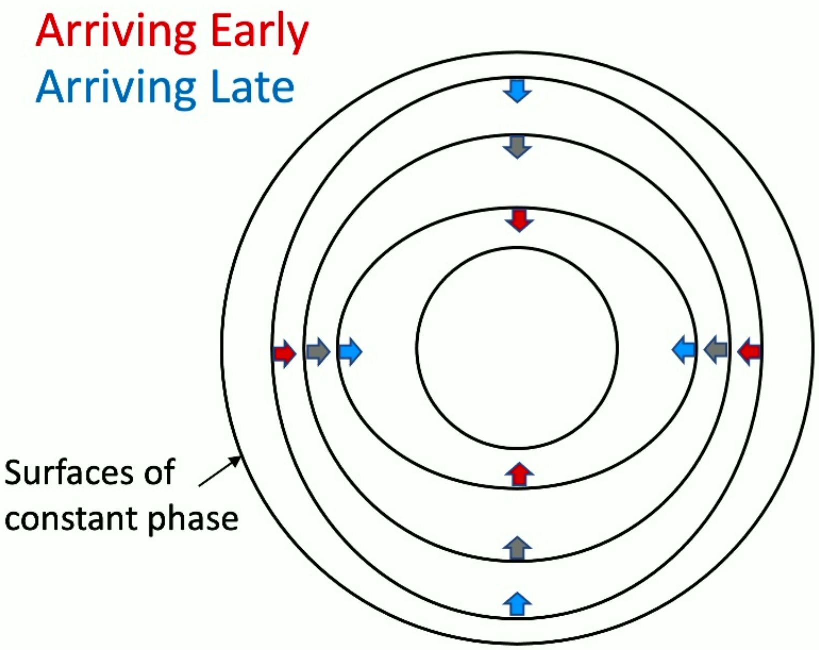
Speculative

Probing Parity Violation in the Stochastic Gravitational Wave Background with Astrometry

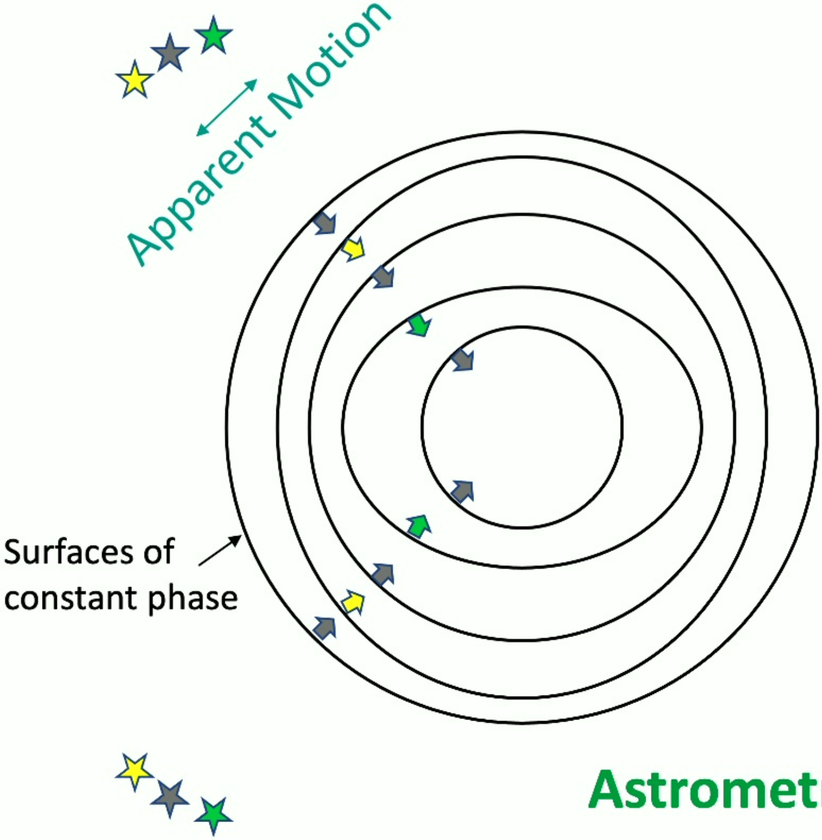
Qiuyue Liang, Meng-Xiang Lin, Mark Trodden, Sam S. C. Wong

astro-ph > arXiv:2309.16666

Effects of passing GW on single observer

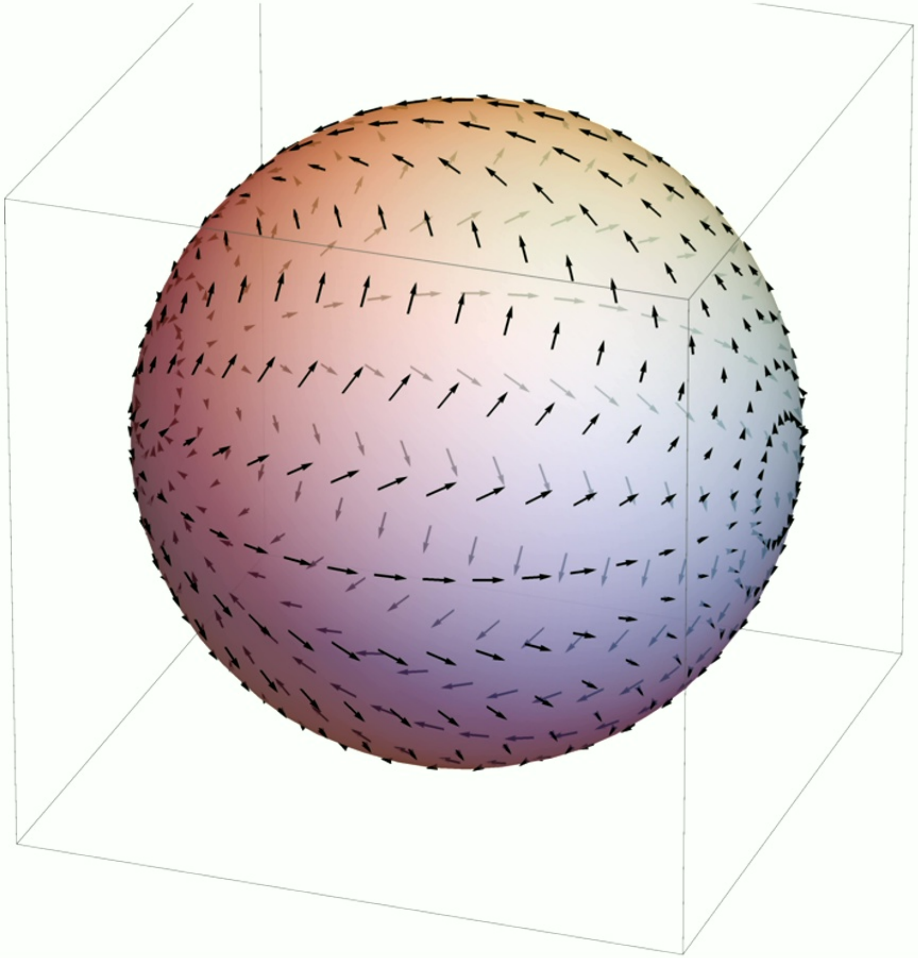


Pulsar Timing

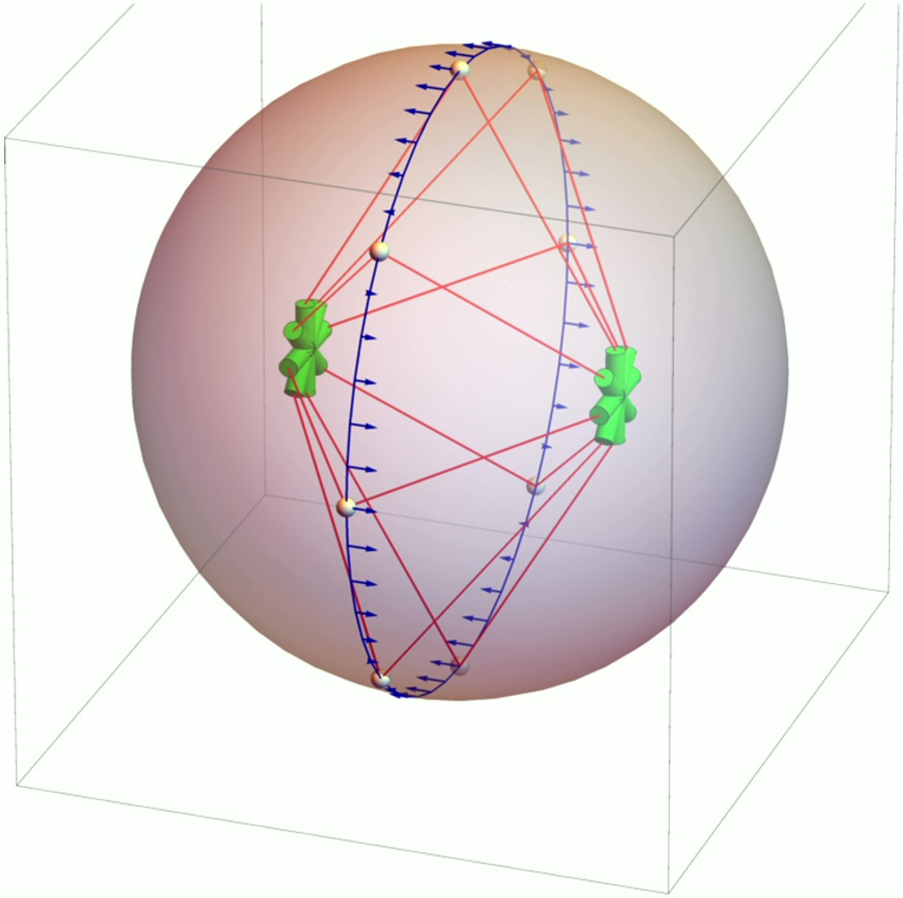


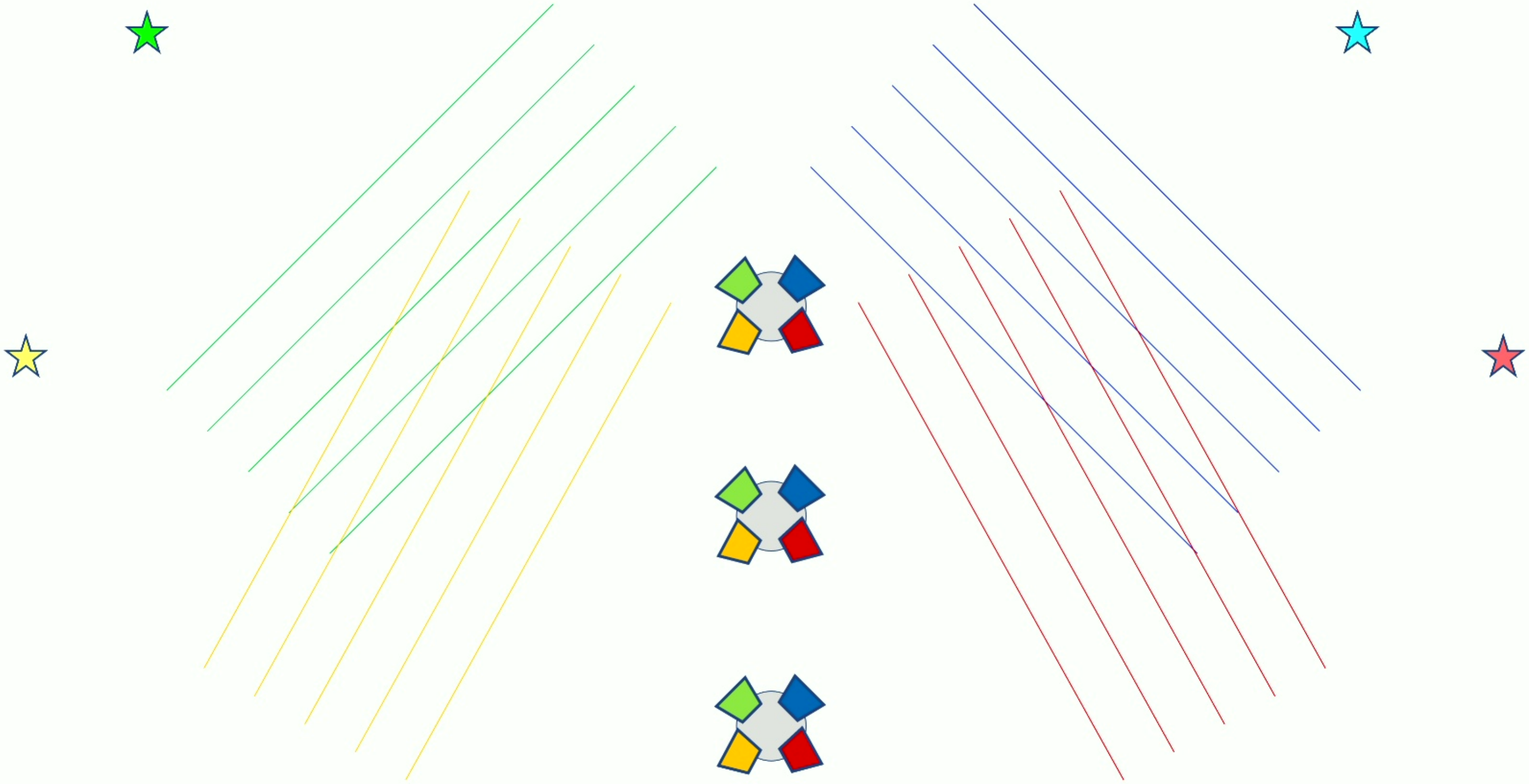
Astrometry

Pattern of apparent motions across the sky sphere (exaggerated by approx. 10^{14})



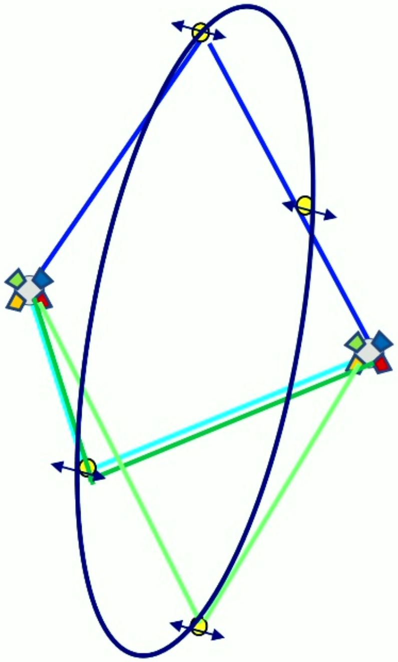
Deflections along interferometer axis and around great circle show unique quadrupolar pattern.

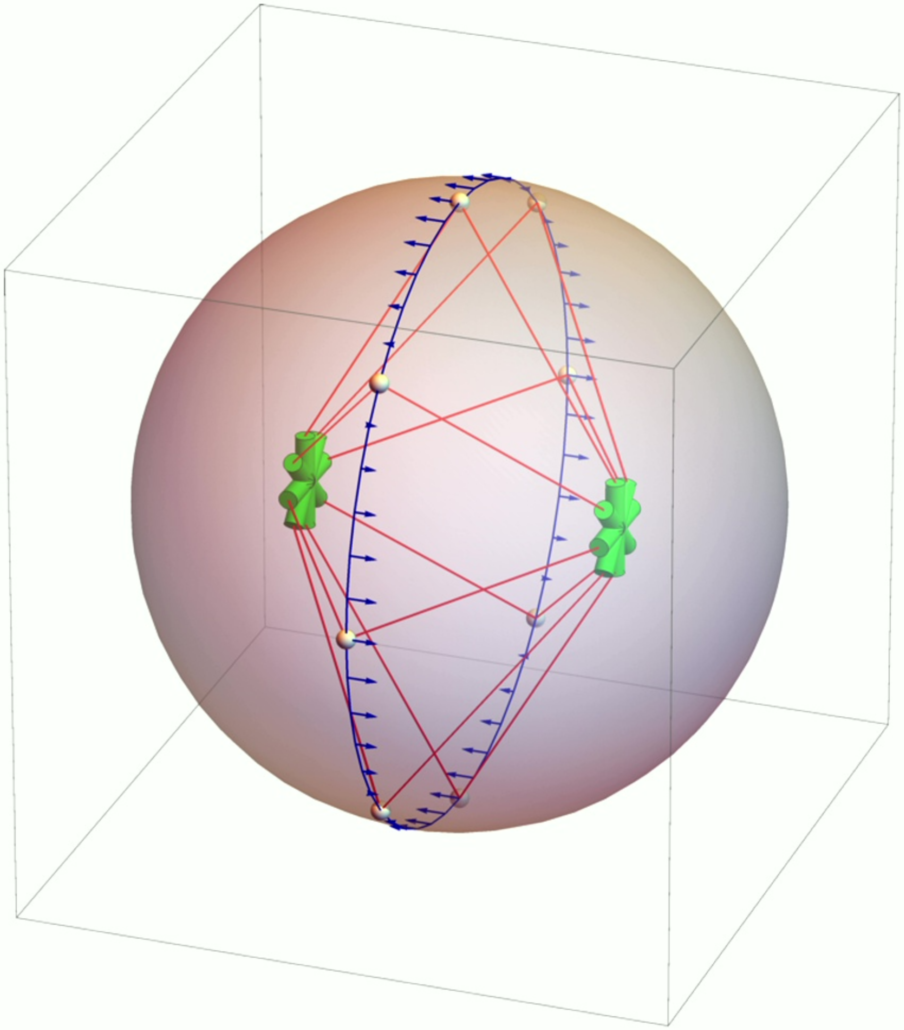




Interferometry 2:

A fleet of pair observatories using SNSV protocol (generalized HBT) on multiple star pairs.



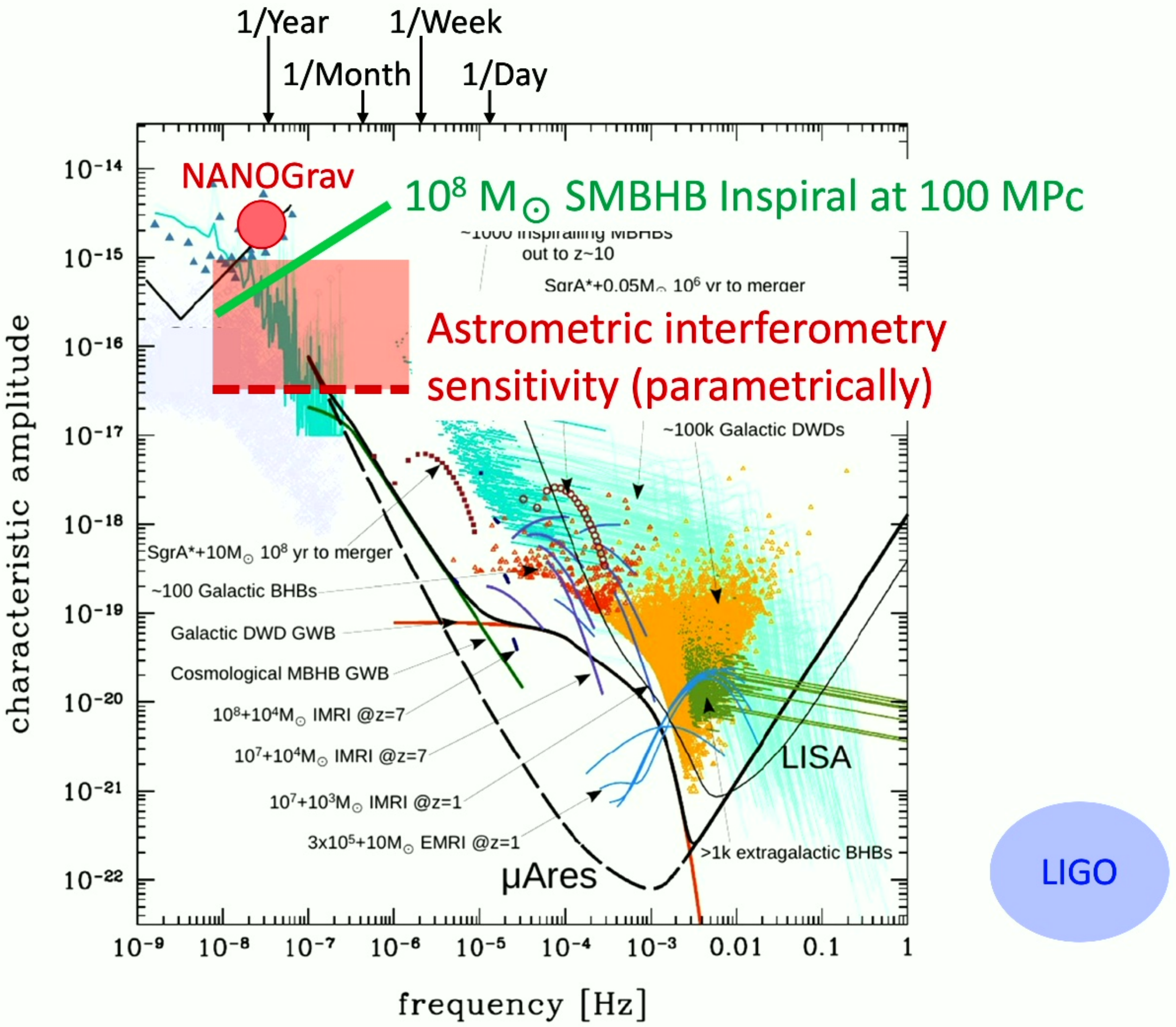


Parametric Sensitivity Scaling

$$h_{\text{Photon Noise}} \sim \frac{\lambda}{B\sqrt{N_{\text{Pairs}}}}$$

Straw-Person numbers:

$\lambda \sim 10^{-6}$ m
B ~ 10^{3} m
Mag ~2 target stars
~100 stations
~10^{4} spectral bins
~15 psec timing
~1m^{2} collecting area
~3 years operation
Sensitivity $h \sim$ few 10^{-17}

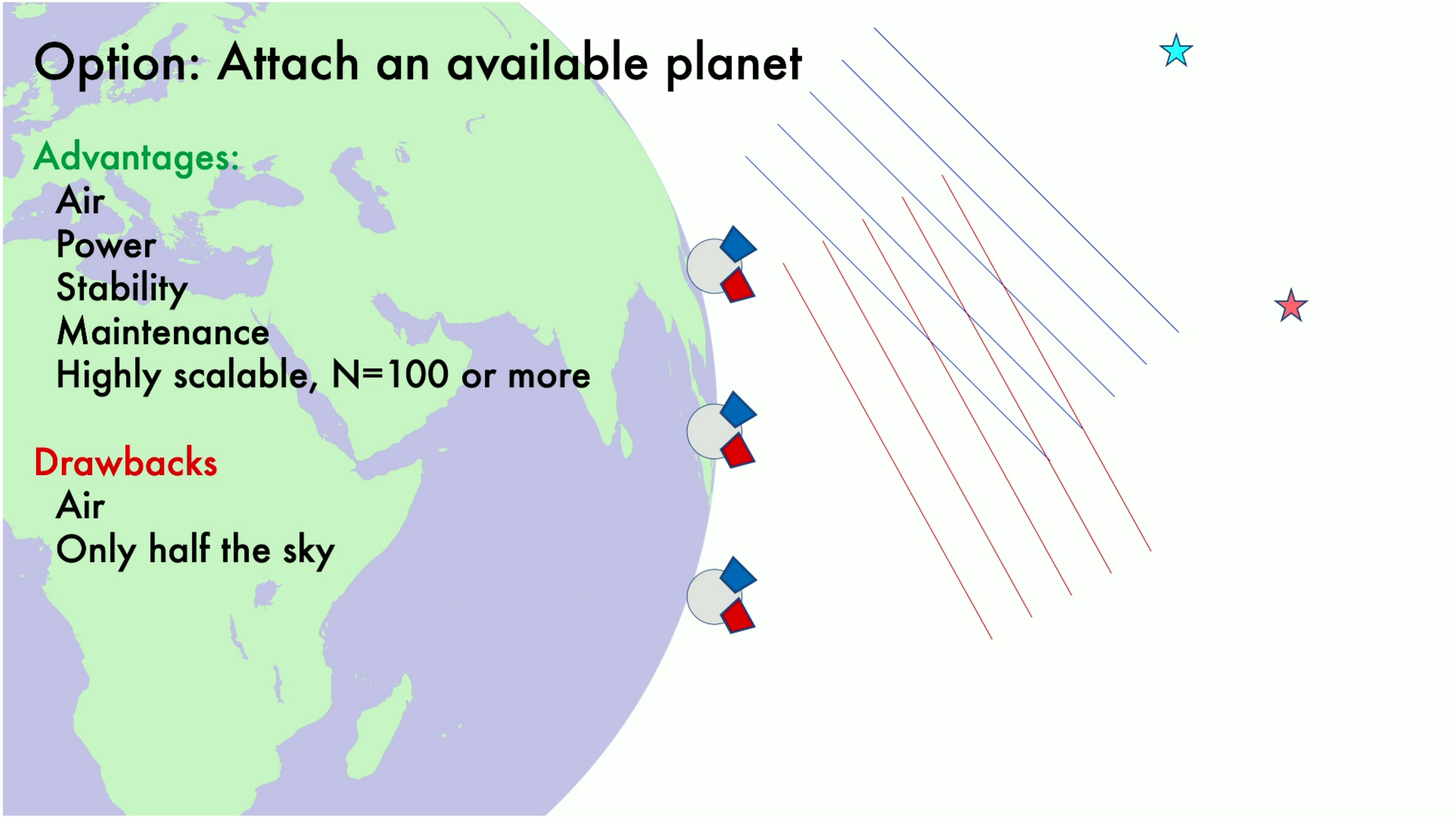


NANOGrav

$10^8\ M_\odot$ SMBHB Inspiral at 100 MPc

Astrometric interferometry sensitivity (parametrically)

Option: Attach an available planet



Advantages:

- Air
- Power
- Stability
- Maintenance
- Highly scalable, N=100 or more

Drawbacks

- Air
- Only half the sky

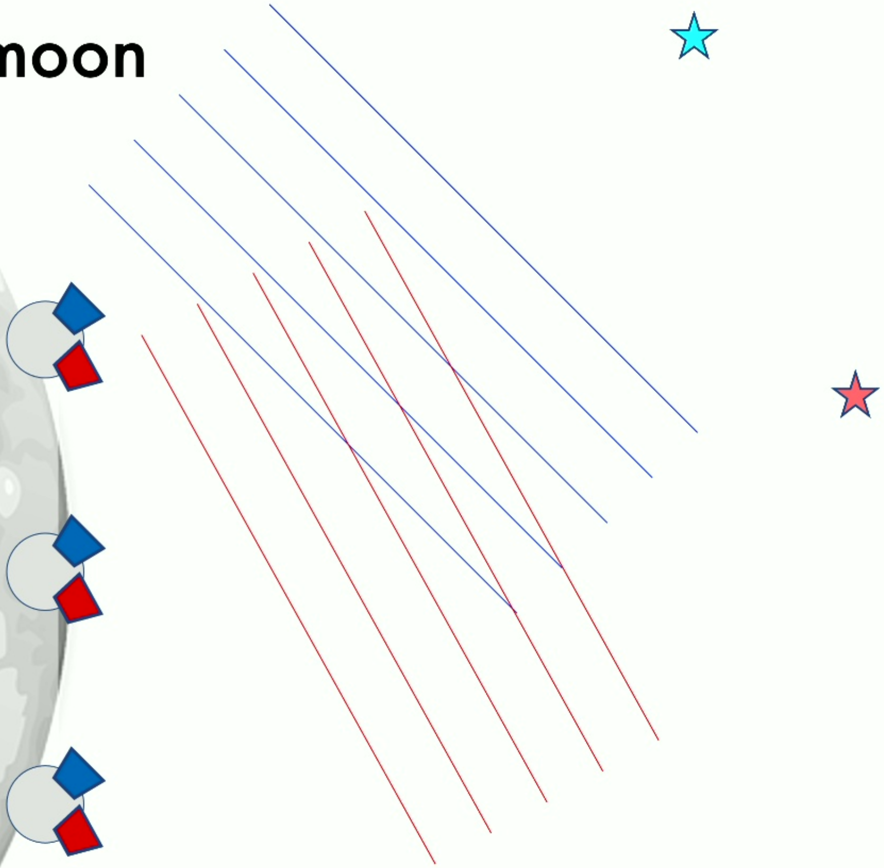
Option: Attach an available moon

Advantages:

- No Air
- Stability
- Slow rotation
- Somewhat scalable?
- Free ride?

Drawbacks

- Only half the sky
- Remote operation
- Low-power nights



Points to take home

- New ("SNSV") method for wide-angle precision astrometry
  - Generalization of both Gottesman protocol and HBT intensity interferometry
  - Arbitrary baselines with no inter-station optical paths needed
  - Depends on coincident pairs, need bright objects or large/many collectors
- Precision astrometry enables gravitational wave search!
  - Can reach physically interesting levels of strain sensitivity
  - Quad-Michelson approach in space; needs much lower level of formation flying precision than previous proposals
  - SNSV pair approach is highly scalable can be done space-based or ground-based
  - Michelson + quantum interesting for many-aperture ground-based approach (ask me later)

Interested? Contact me stankus@bnl.gov