Toward Large Arrays, Small Exoplanets, and Long Gravitational Waves

Paul Stankus, BNL

In association with A. Nomerotski, A. Slozar, S. Vintskevitch, N. Bao, J. Haupt, B. Farella, A. Mueninghoff, Z. Chen, M. Keach, S. Bellavia, R. Abrahao, J. Crawford, J. Martinez, et.al.

Quantum Enhanced Telescopy Workshop, Quantum 2.0, June 18, 2023

Brookhaven™ National Laboratory

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

See also:

QM2B

10:30 - 12:00 Mountain Time, Monday

Quantum Astronomy

Presider: Paul Kwiat, *Univ of Illinois at Urbana-Champaign, United States*

Centennial H

11:30 - 11:45
(UTC - 06:00)

QM2B.4

Fast Two-Photon Interferometer Capable of Spectral Binning for Quantum Telescopy

Presenter: Andrei Nomerotski, *Brookhaven National Laboratory, United States*

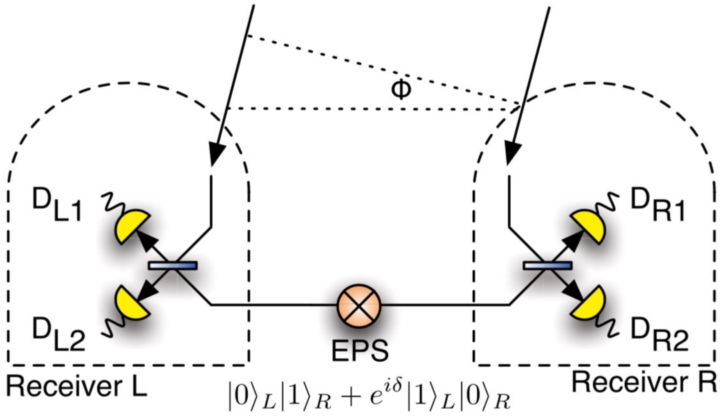
Quantum Telescopy Posters

R. A. Abrahao, BNL: Next Generation of Spectrometers for Quantum-assisted Astronomy

A. Mueninghoff, SBU/BNL: Towards Two-Photon Amplitude Interferometry and its Cosmological Applications

Entanglement-Assisted Michelson

Quantum networks



PRL 109, 070503 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Longer-Baseline Telescopes Using Quantum Repeaters

Daniel Gottesman[*]

Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

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Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, Canada

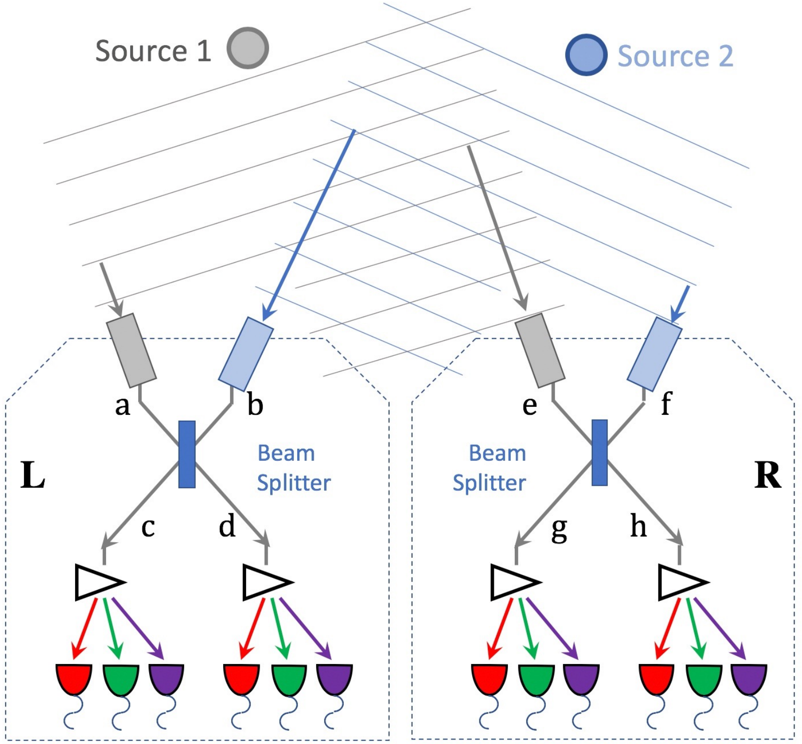
Sarah Croke[‡]

Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

(Received 25 October 2011; revised manuscript received 22 May 2012; published 16 August 2012)

Two-source, generalized HBT

Arbitrary baselines



Instrumentation and Methods for Astrophysics

Vol. 5, 2022 · November 01, 2022 IST

Two-photon amplitude interferometry for precision astrometry

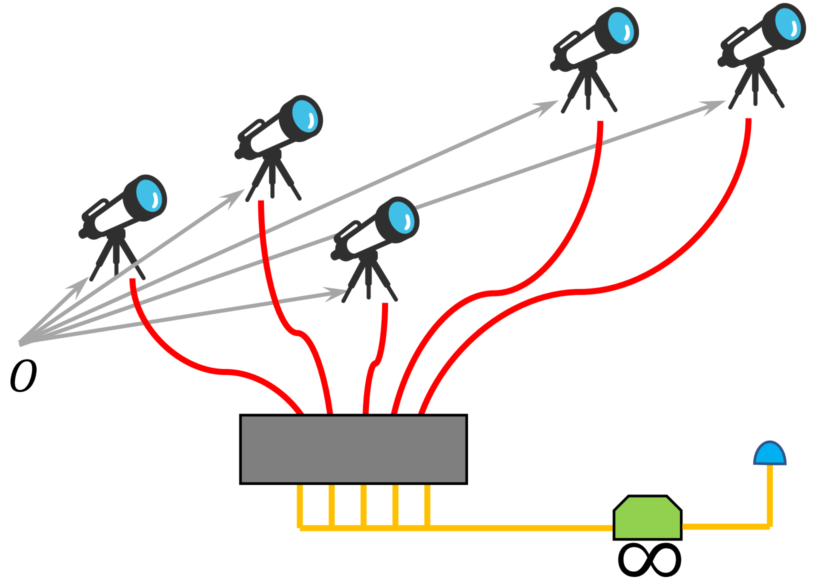
Paul Stankus , Andrei Nomerotski , Anže Slosar , Stephen Vintskevich

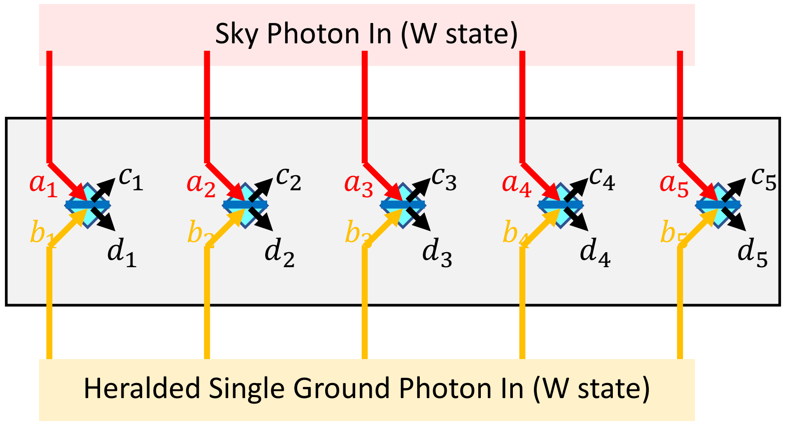
https://doi.org/10.21105/astro.2010.09100

Astronomical Instrumentation | Astrometry | Quantum Physics | Inteferometry | Interferometric Correlation

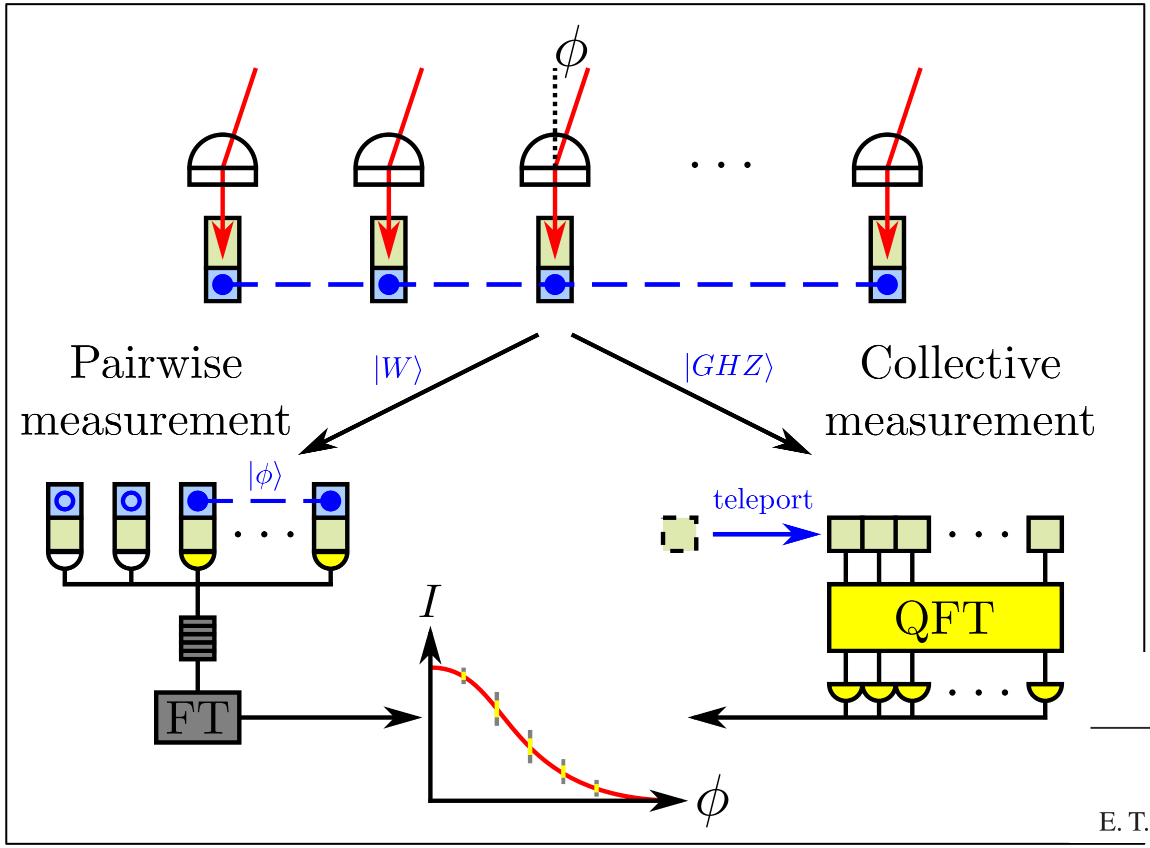
Very Large Arrays

Higher rates, multipartite states; factor $O(N)$ QuAdv





General: Quantum network allows to *separate* the tasks of *collecting* astronomical photons from that of *transporting and processing* them



Let’s assume it all works; what kind of physics can we do?

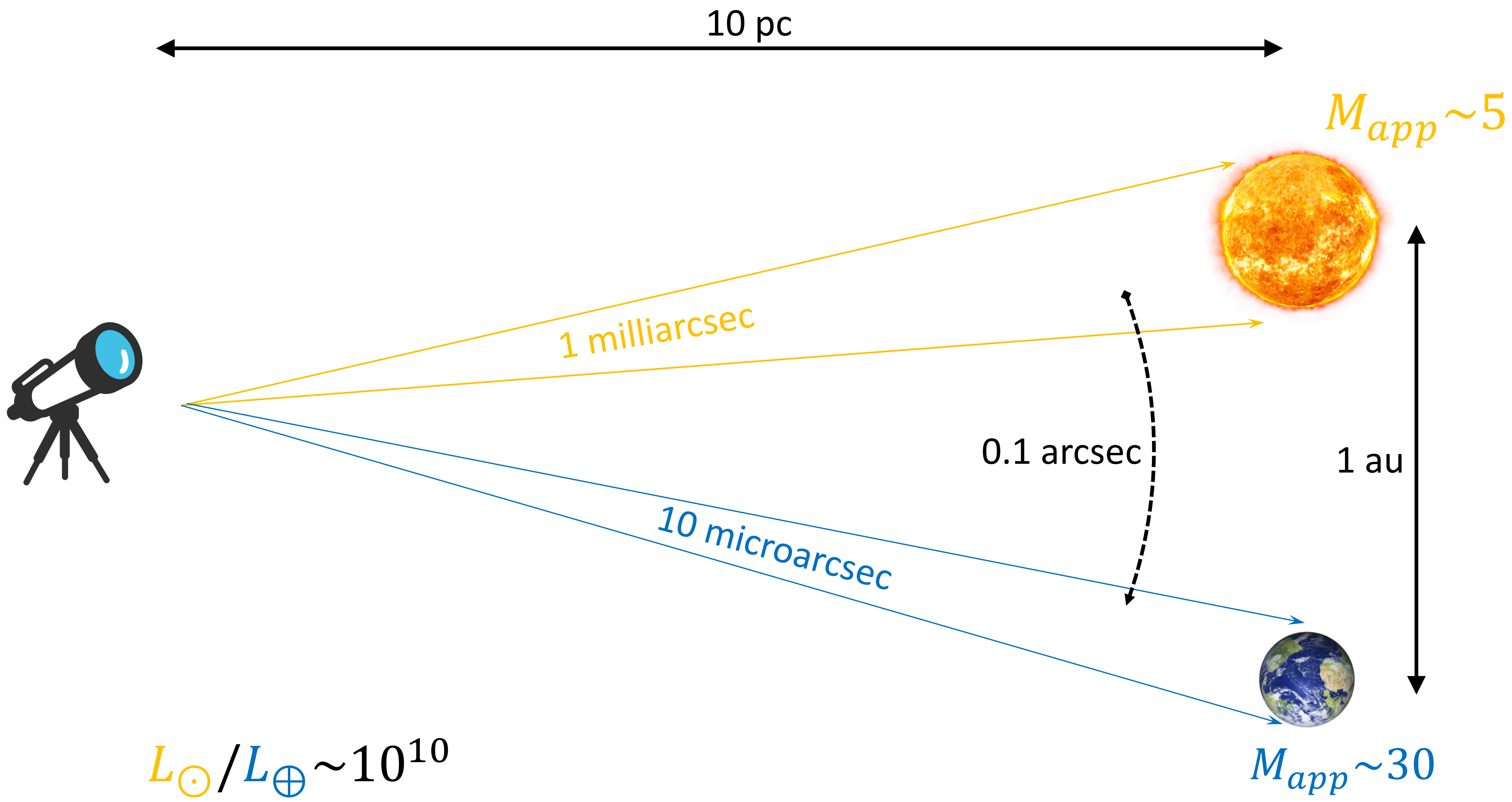
PHYSICAL REVIEW LETTERS **123,** 070504 (2019)

Optical Interferometry with Quantum Networks

E. T. Khabiboulline,[1,*] J. Borregaard,[1,2] K. De Greve,[1] and M. D. Lukin[1]

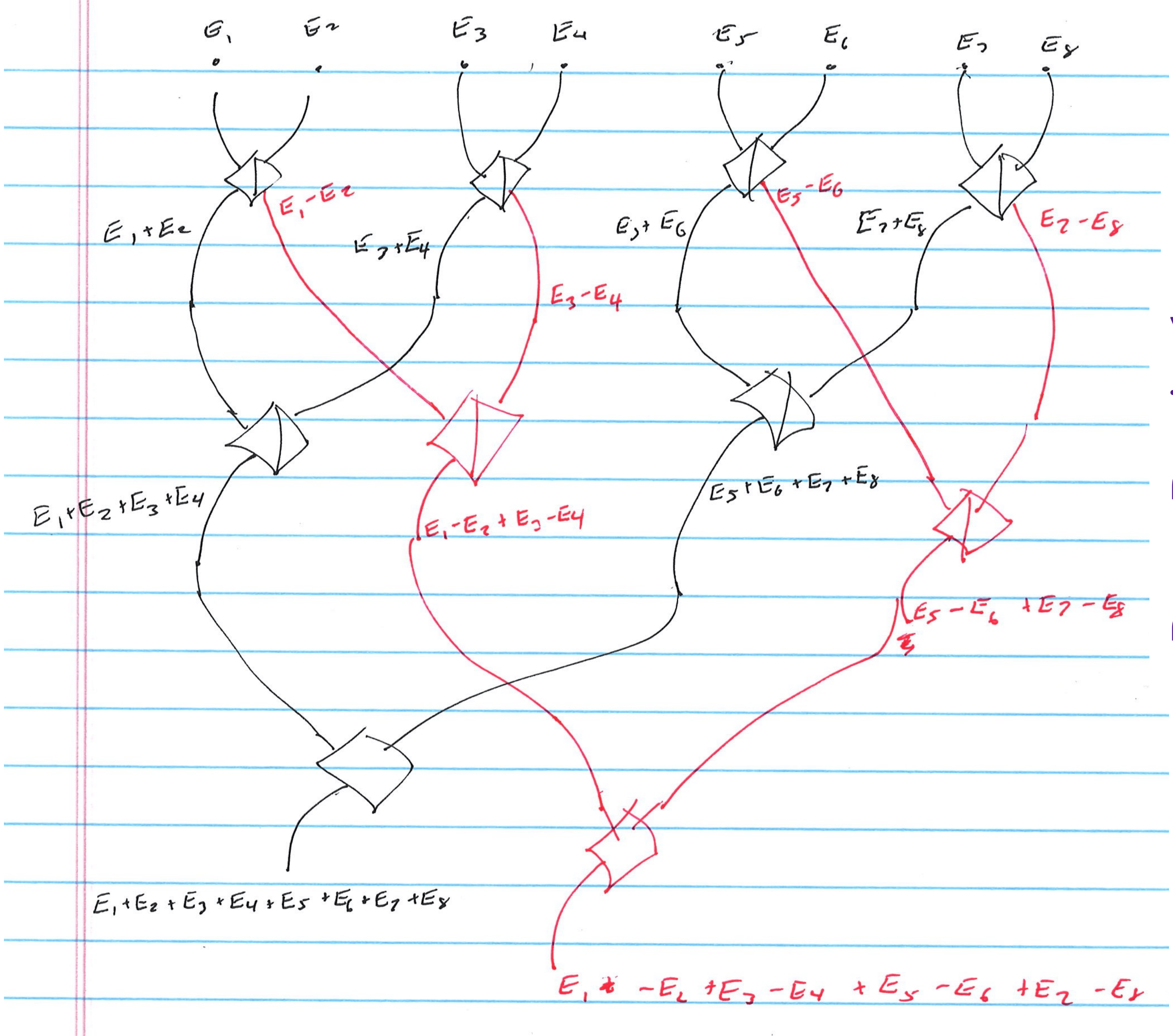
Large array aperture and **apodization synthesis** for exoplanet spectra and imaging

Toward the goal of observing Earth-like exoplanets

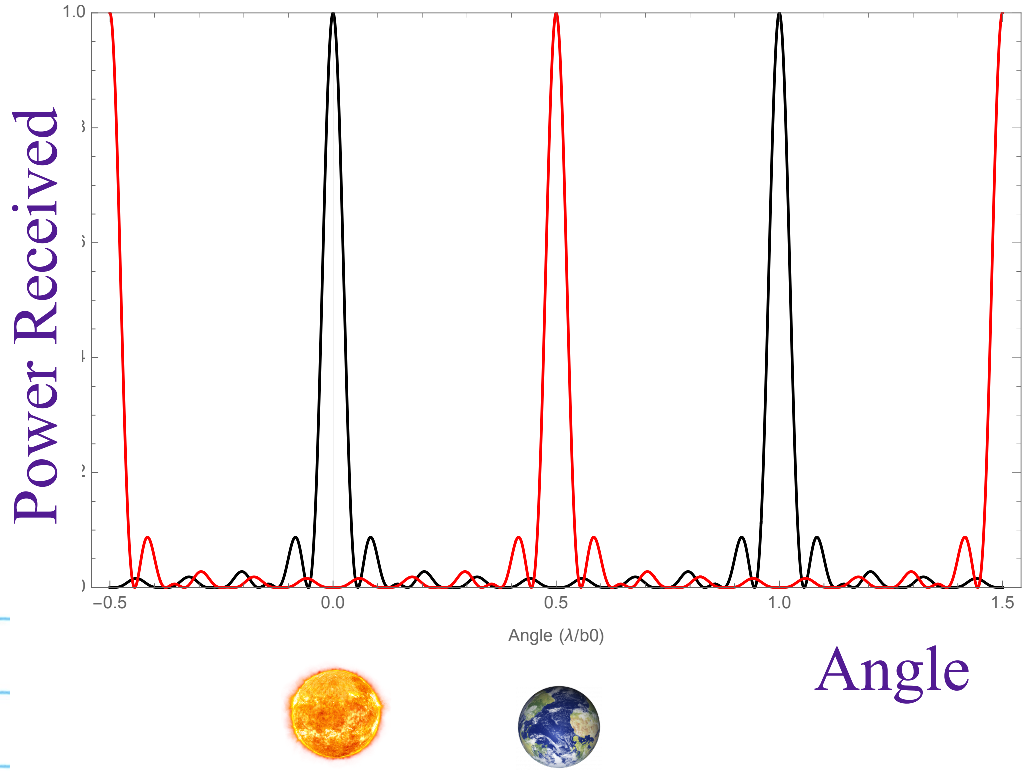


10 pc
M_{app}~5
1 milliarcsec
0.1 arcsec
1 au
10 microarcsec
$L_{\odot}/L_{\oplus}$~10^{10}
M_{app}~30

Idea: a 1-D optical interferometric array

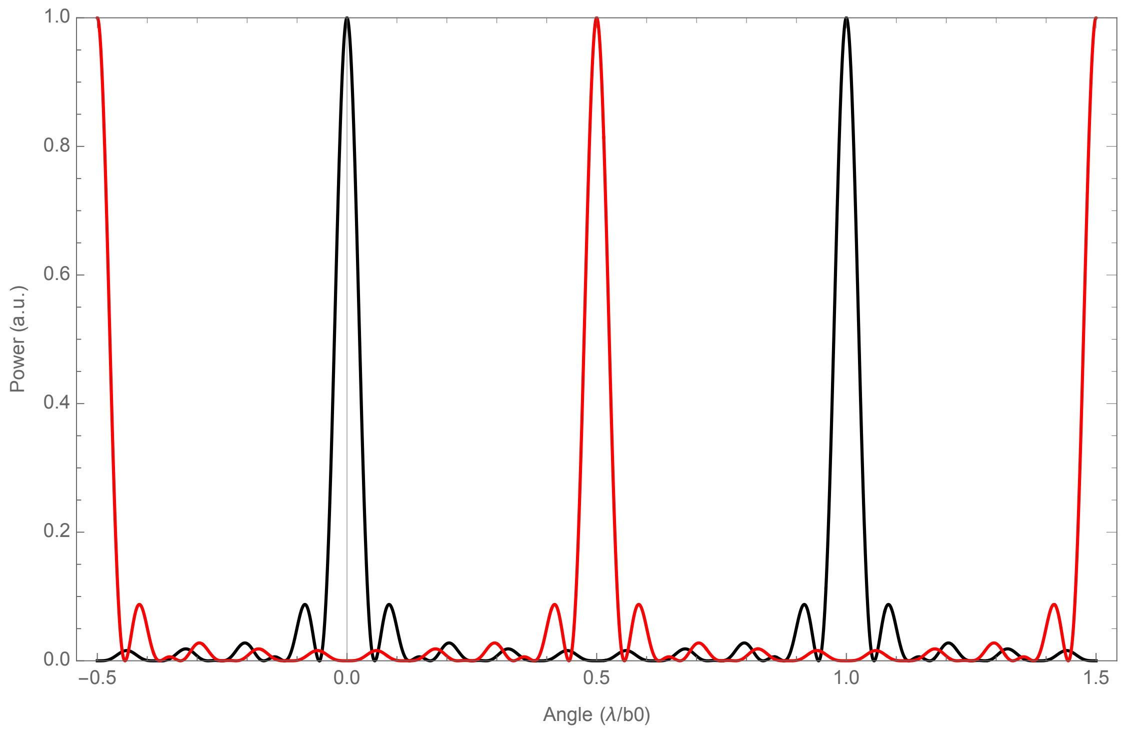


The all-positive sum has a narrow main beam (black), and the alternating positive negative sum has the complementary main beam (red)

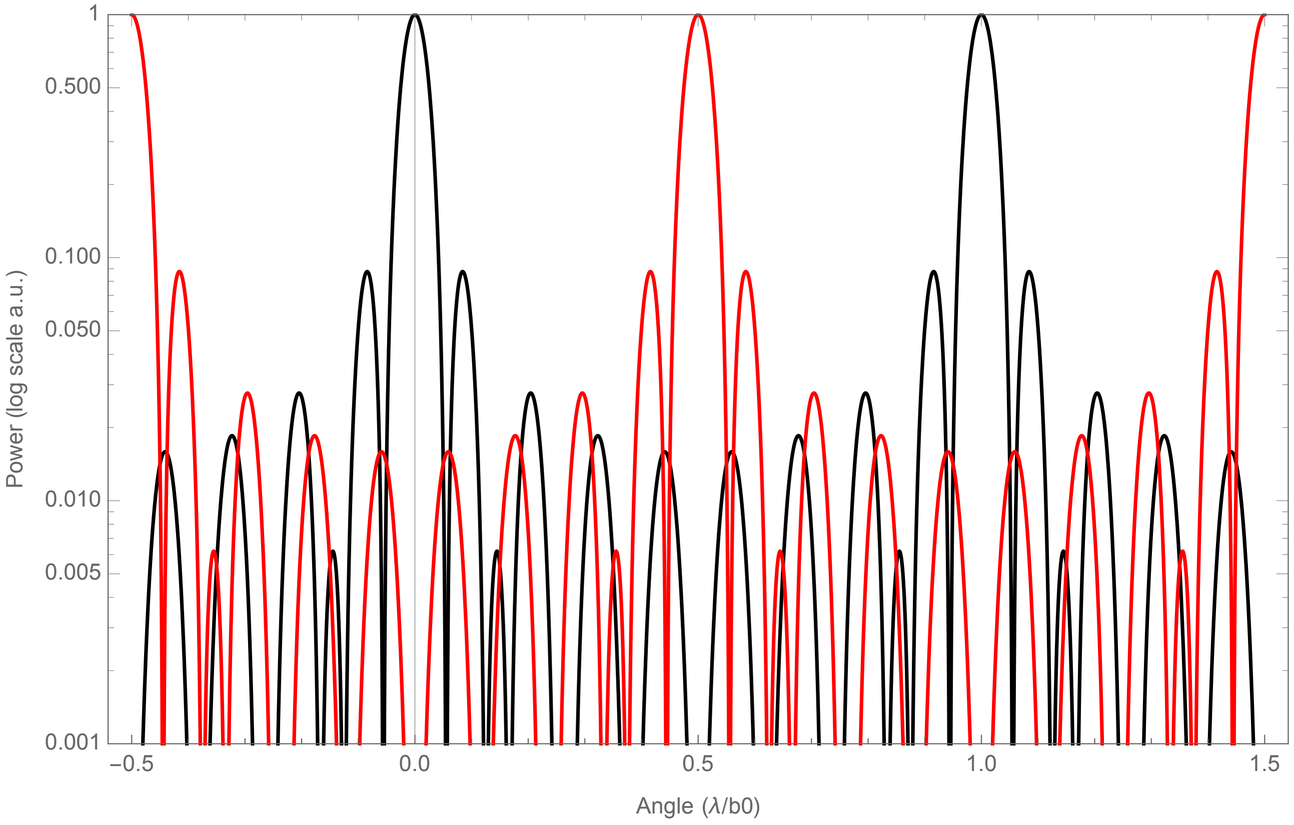


Not a new idea; see "kernel nulling"…

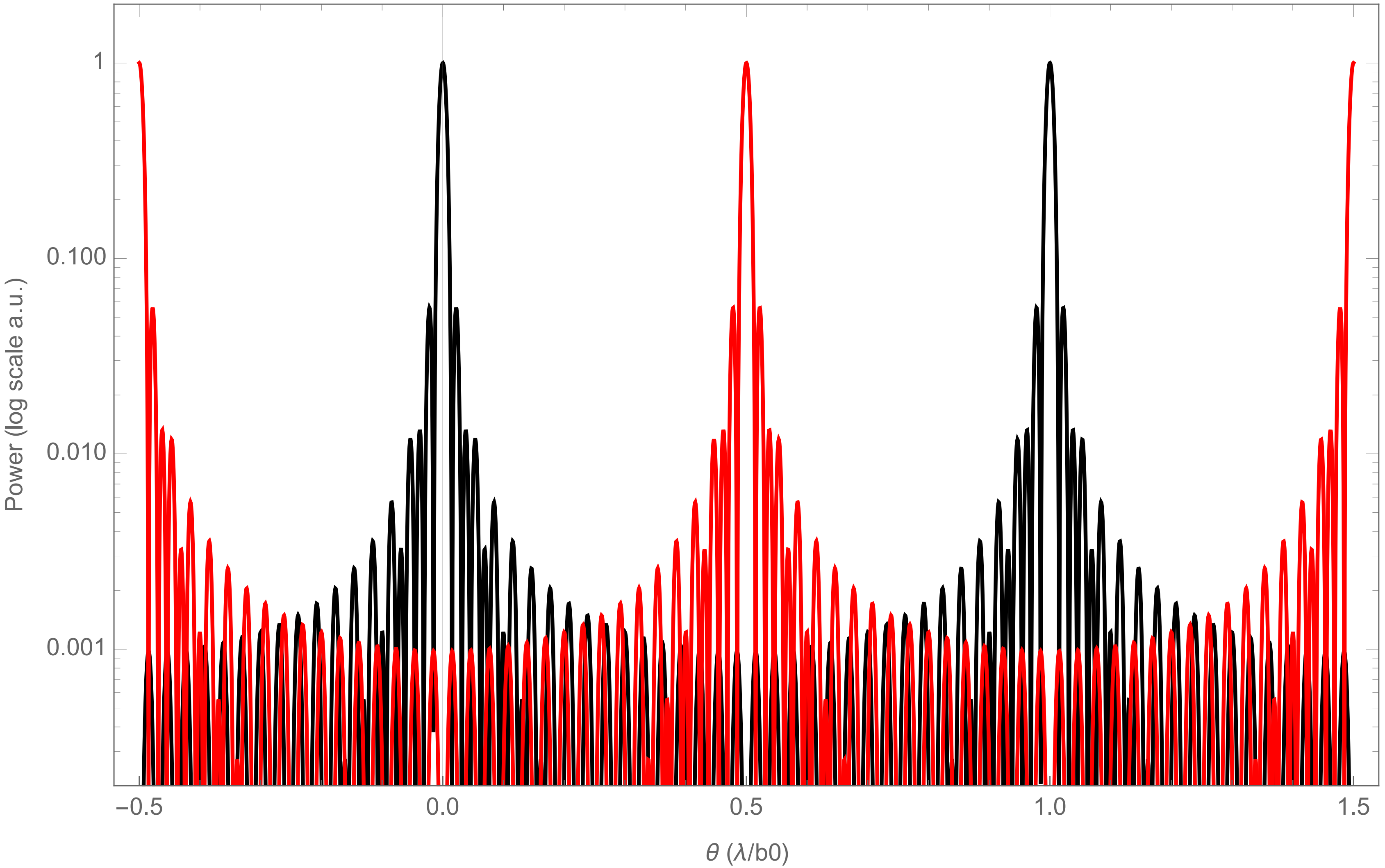
Linear



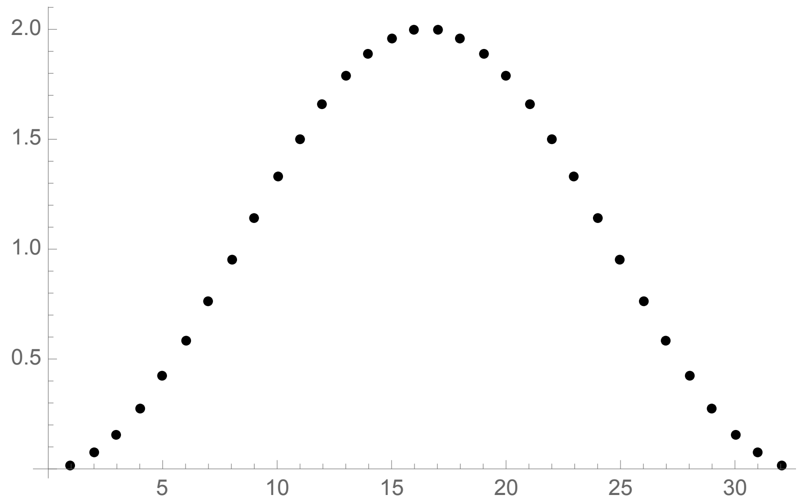
Semi-Log



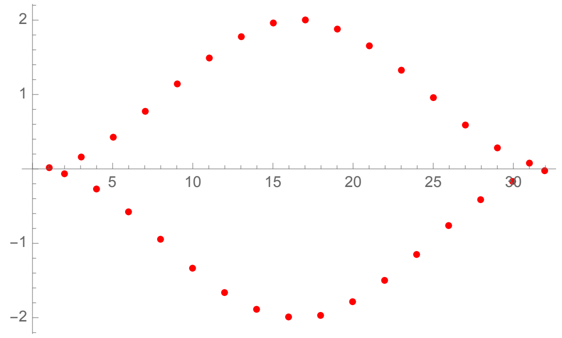
Plotting the power receptivity on a log scale allows us to see that, while one beam has a null where the other has a maximum the general level of the suppressed beam is on the order of 1/100.

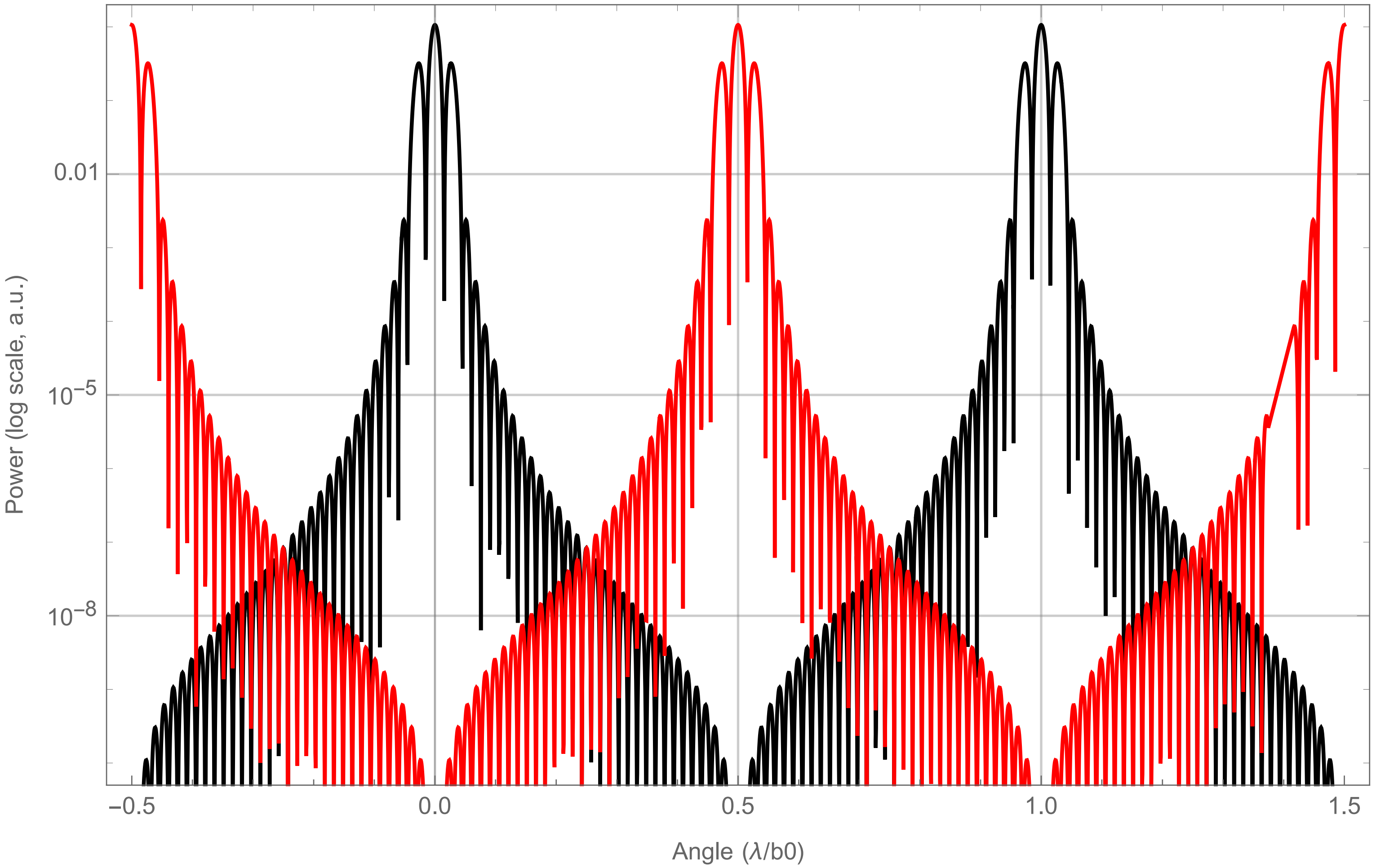


Idea 1: Improvement with larger arrays. We can improve the suppression of each beam in the area of its minimum by increasing the number of apertures; but only slowly. The beams for 32 apertures shown here have narrower main lobes but only a ~10^{-3} suppression near their minima.



Tapered weighting pattern for each of 32 apertures. This is at the E field level, not the power level; so the same pattern but alternating in sign (below) applies to the alternating sum.





Idea 2: Improvement with tailored coupling. We can increase the suppression at the minimum, at the cost of broadening the main lobe, by *tapering*, ie selectively attenuating the incoming beams (akin to the PFB). The tapering pattern shown here produces the 10^{-10} suppression/contrast we would need to separate the light from Earth versus the Sun.

Precision stellar astrometry for mid-frequency gravitational wave detection

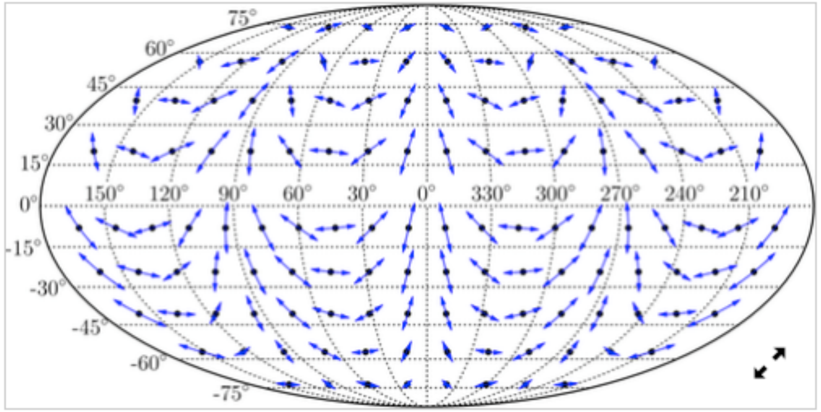
Gravitational waves shake the sky – by a tiny, tiny, bit

FOCUS

Detecting Gravitational Waves by Watching Stars

December 29, 2017 • *Physics* 10, 138

A passing gravitational wave produces shifts in the apparent positions of the stars, and these motions should be detectable with the Gaia space telescope.



C. J. Moore/Univ. of Cambridge

Reading the stars. A low-frequency gravitational wave passing through Earth's neighborhood would cause the positions of distant stars (black dots) to appear to oscillate slightly over time. The pattern can reveal the wave's amplitude, frequency, and polarization. The motions are exaggerated here for clarity. Show Less

Astrometric Search Method for Individually Resolvable Gravitational Wave Sources with Gaia

Christopher J. Moore, Deyan P. Mihaylov, Anthony Lasenby, and Gerard Gilmore

Phys. Rev. Lett. 119, 261102 (2017)

Published December 29, 2017

Recent Articles

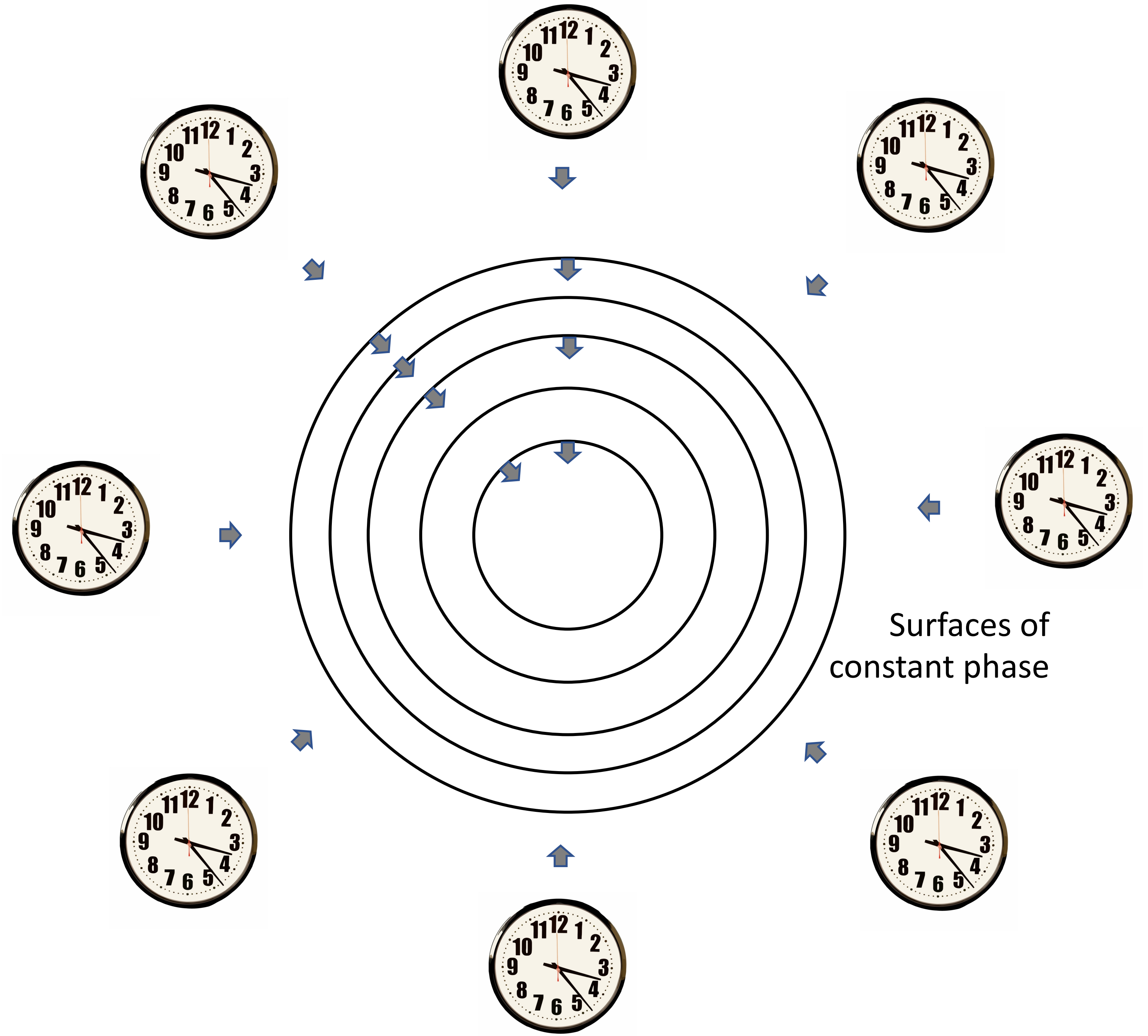
Phonons on the Splitting Block

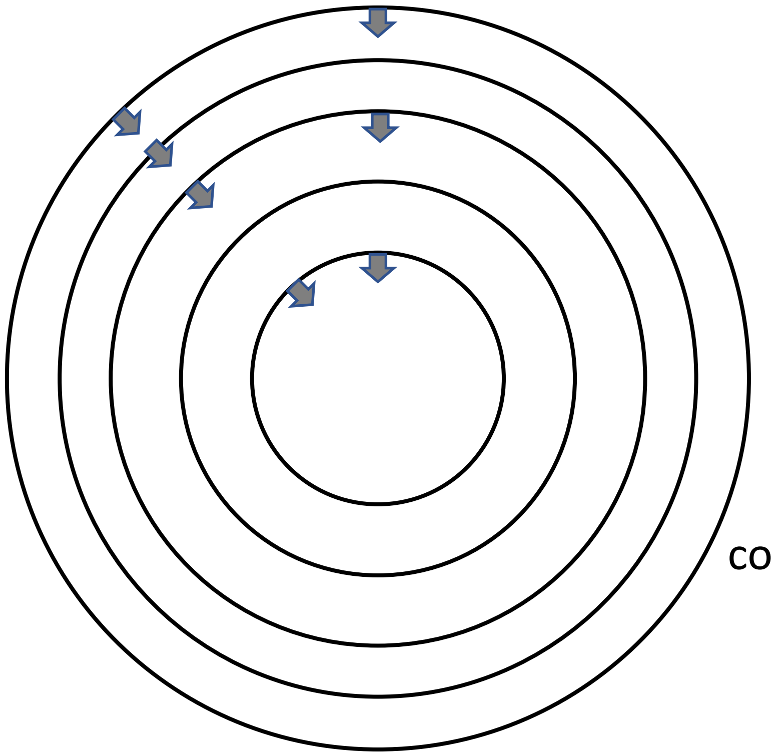
Using a "bad" acoustic mirror, physicists demonstrate a phonon beam splitter, a device that could one day be used to make phonon-based quantum logic gates.

Excited Sodium-32 with a Spherical Wave Function

Researchers may have found an unstable sodium nucleus that has an excited state with a spherical wave function—an elusive prospect for the study of nuclear shapes.

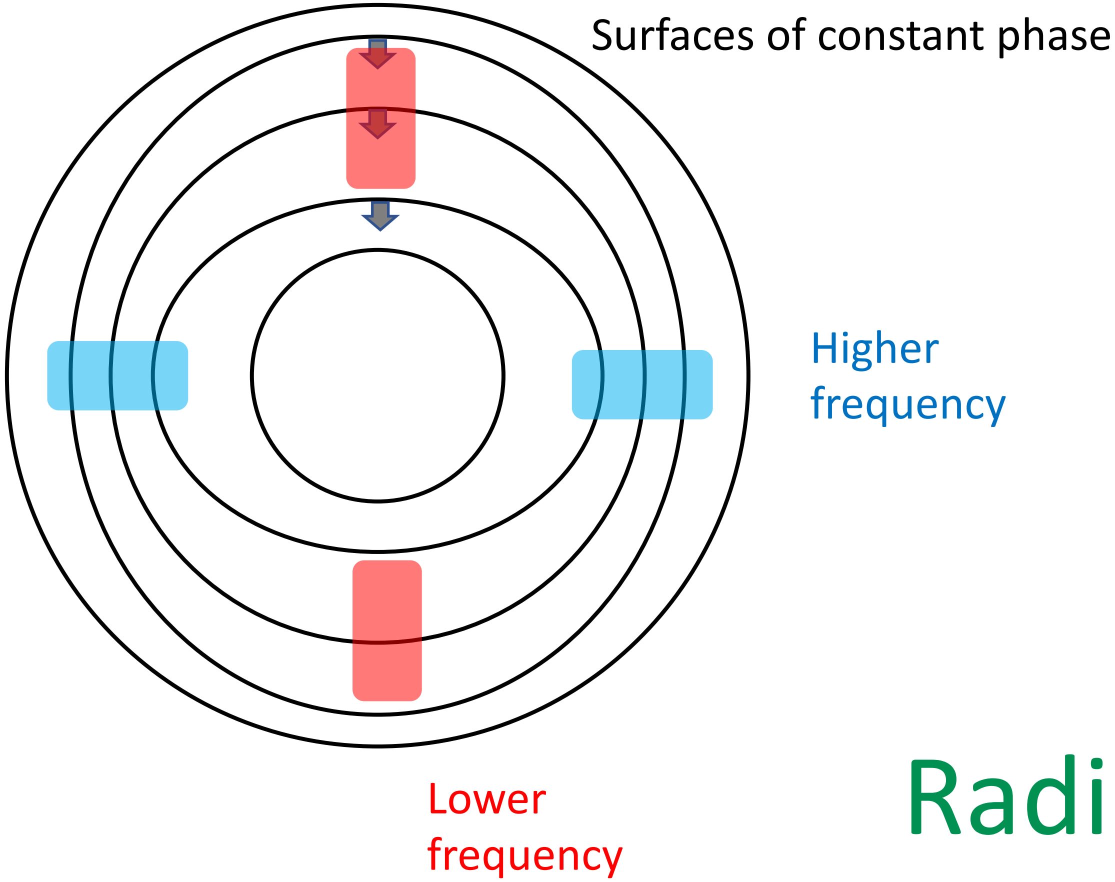
A Different Angle on the Color Glass


Surfaces of
constant phase


Surfaces of
constant phase

Effect of passing gravitational wave

Basic result: if a GW is passing by the observer then an alternating quadrupolar pattern of red/blue shifts is seen from distance sources.



Hellings and Downs 1983

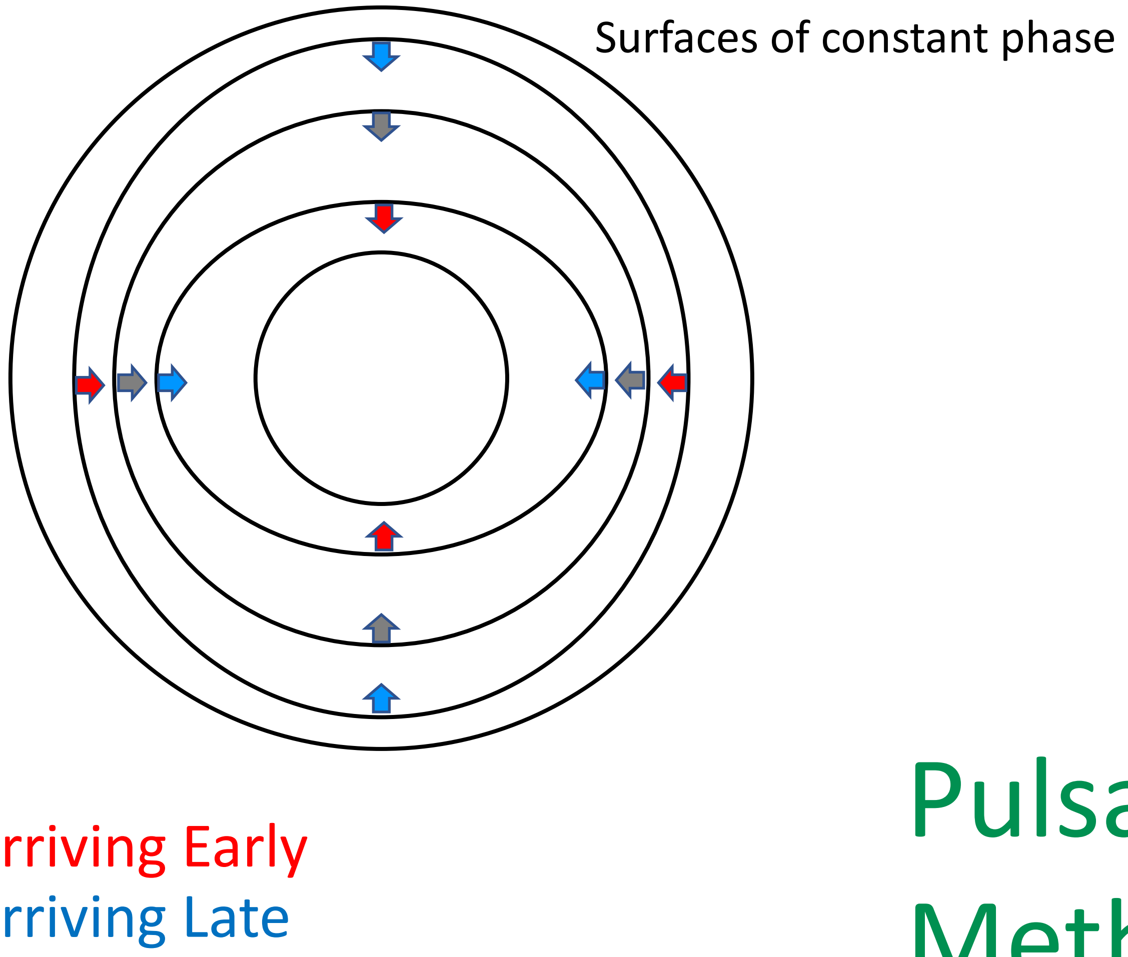
in the pulse frequency, $\nu = 1/P$, to be (see Estabrook and Wahlquist 1975; Hellings 1983)

$$\frac{\Delta\nu}{\nu} = \frac{1}{2}\cos 2\phi[1 - \cos\theta] \times [h(t) - h(t - l - l\cos\theta)], \qquad (1)$$

where l is the Earth-pulsar distance at an angle θ to the propagation direction (z-axis), and ϕ is the angle be-

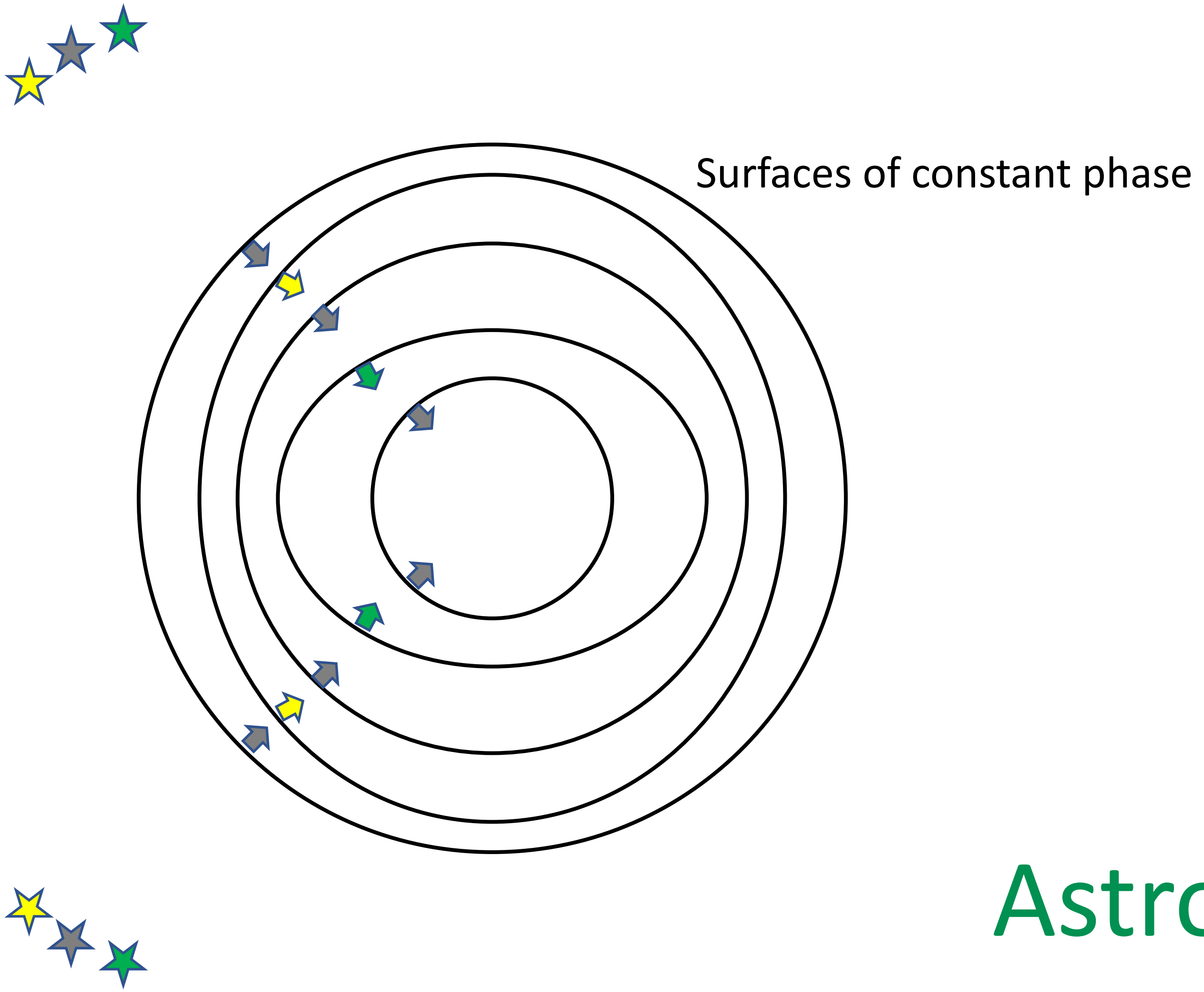
Radial Doppler Method

If we track individual arriving wave/pulse fronts then we see an alternating quadrupole pattern of early and late arrivals.



Pulsar Timing Method

The surfaces of constant phase are bent along the diagonal directions, which must correspond to a *change in apparent incoming direction*/sky position.



Astrometry Method

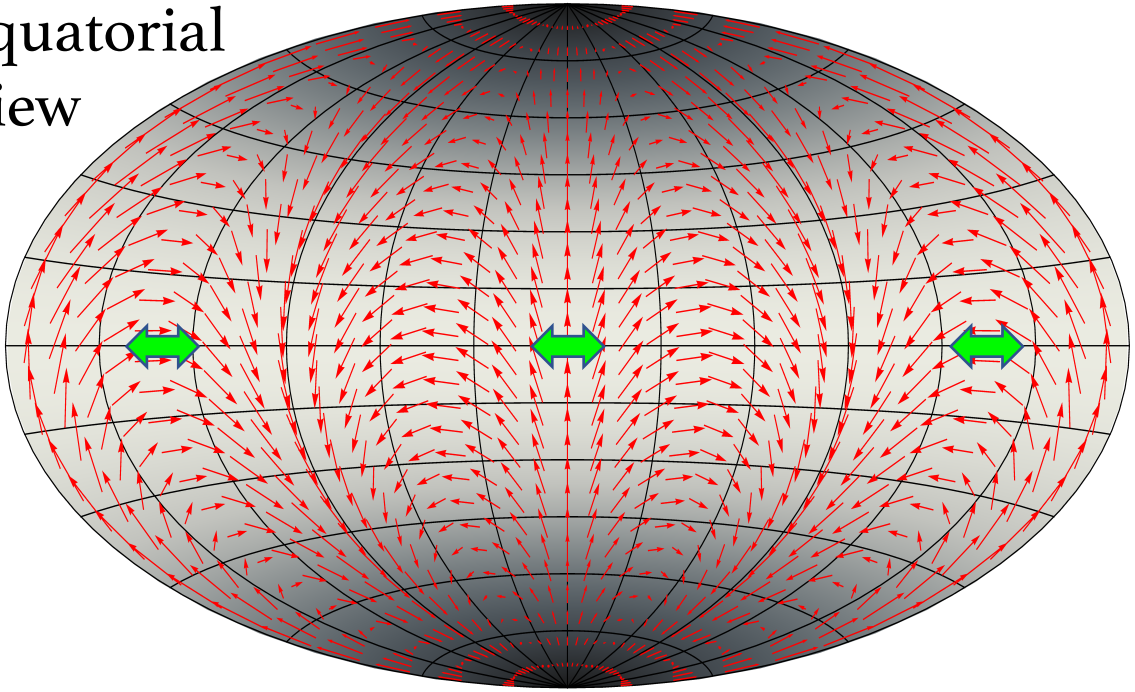
Shaking The Sky

PRL **119,** 261102 (2017) PHYSICAL REVIEW LETTERS week ending 29 DECEMBER 2017

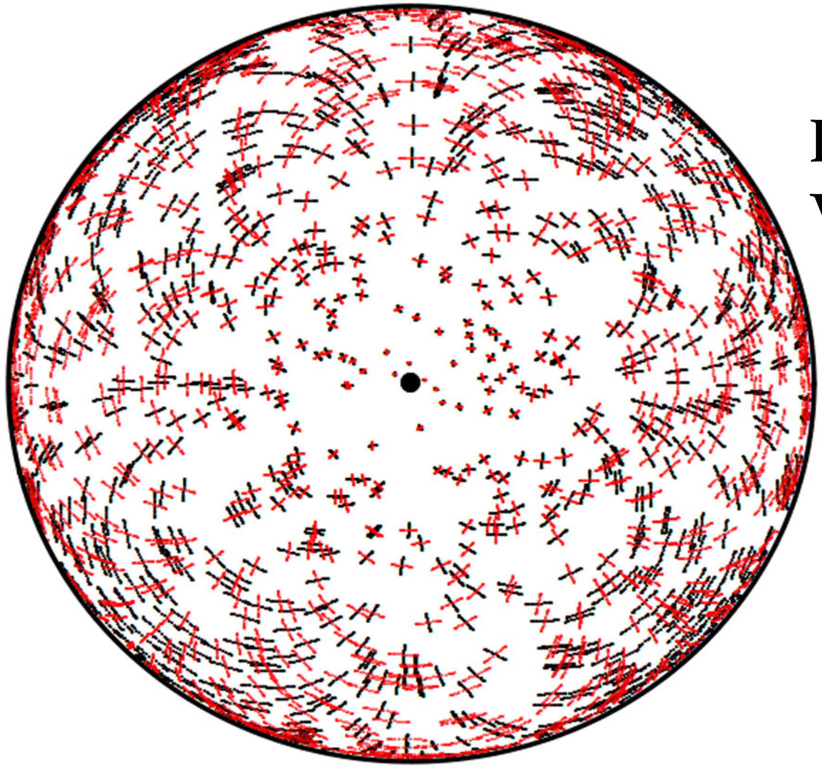
Astrometric Search Method for Individually Resolvable Gravitational Wave Sources with Gaia

Christopher J. Moore,[1,*] Deyan P. Mihaylov,[2] Anthony Lasenby,[3,4] and Gerard Gilmore[2]

Equatorial View



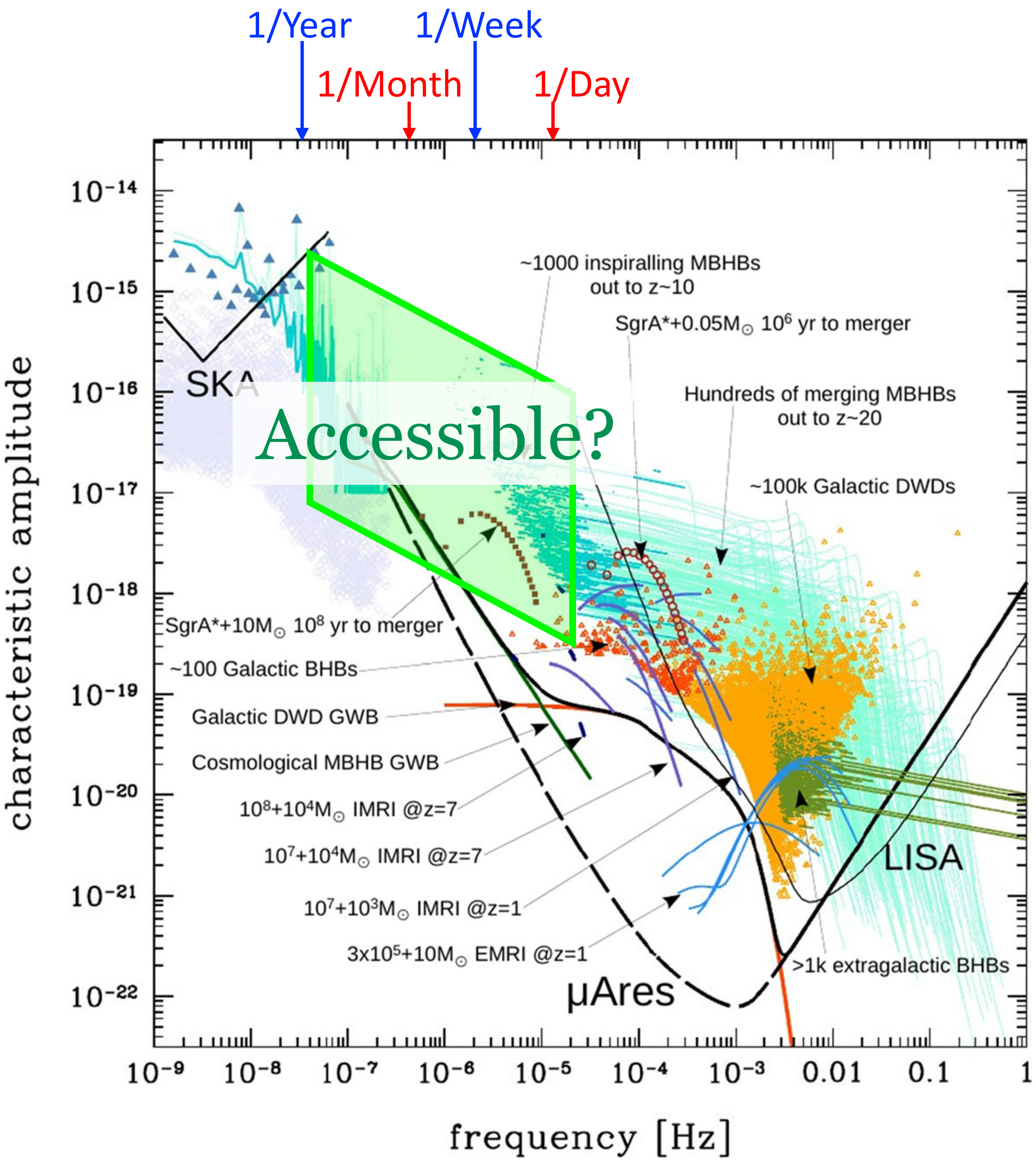
Klioner, arXiv:1710.11474



Polar View

Very distinctive pattern of stellar motions, unlikely to be imitated by systematic effects.

$$\delta n_i = \frac{n_i - q_i}{2(1 - \vec{q} \cdot \vec{n})} h_{jk}(E) n^j n^k - \frac{1}{2} h_{ij}(E) n^j$$



Sirens: Constant, mono-chromatic sinusoid; prime example is SMBH-SMBH slow inspiral over years

Transients: Final SMBH-SMBH merger, or peri-Astron close encounter

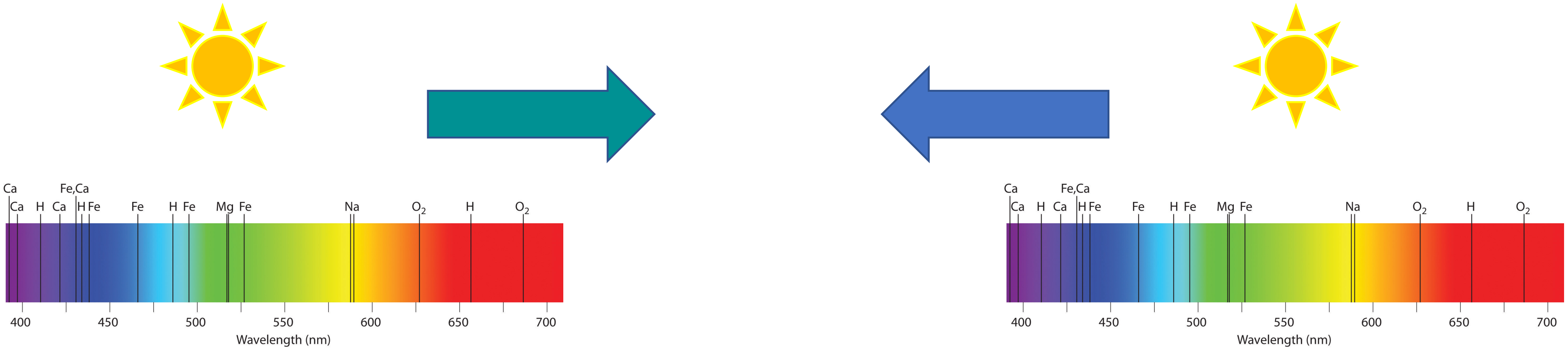
Stochastic: Overlap of many, many small waves from multiple sources

LIGO

A question for all you assembled genii:

Is there a quantum-advantaged way of measuring the relative/differential radial velocity between two stars?

If so then it could open the way for RV GW measurement



Summary

- Extending quantum-assisted astronomy/astrometry to large arrays promises many advantages: large quantum advantage, larger collecting areas, combined with long baselines
- One application of large, regular arrays is aperture synthesis, and also apodization synthesis; could be a path forward for observing small, Earth-like exoplanets
- Gravitational waves create distinct astrometric perturbations that could in principle be measured with precision stellar observation