Coherence in the sky: precision astrometry with intensity interferometry

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Masha Baryakhtar

Bay Area Theory Meeting

March 15, 2024

Laboratories in the Sky: New Physics from the Stars

Throughout the ages, the stars have taught us about the fundamental constituents of the universe and our place in it

Laboratories in the Sky: New Physics from the Stars

Hipparchus: cataloged hundreds of stars to 1° precision (angular size of the moon)

Discovered Earth's precession

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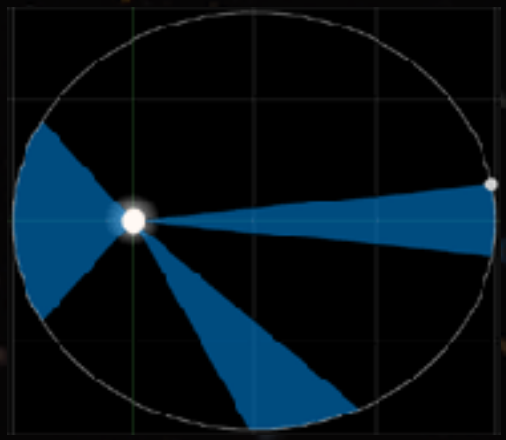


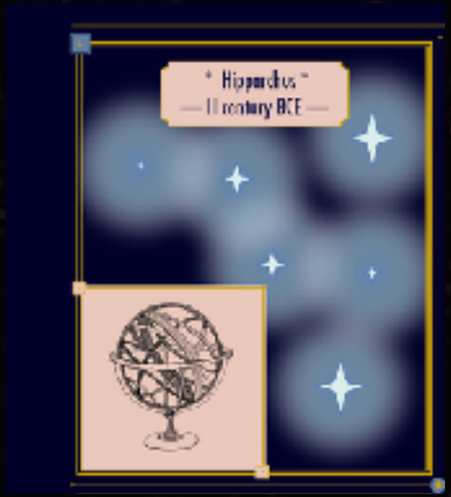
Tycho Brahe: cataloged a thousand stars to 1' precision (size of Venus)

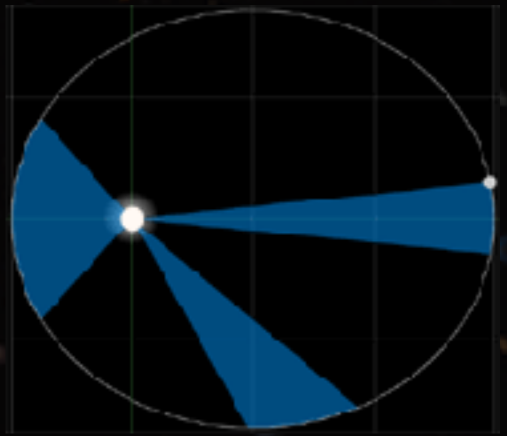
Kepler: Established laws of planetary motion

Laboratories in the Sky: New Physics from the Stars

Hipparchus: cataloged hundreds of stars to 1° precision (angular size of the moon)

Discovered Earth's precession





Tycho Brahe: cataloged a thousand stars to 1' precision (size of Venus)

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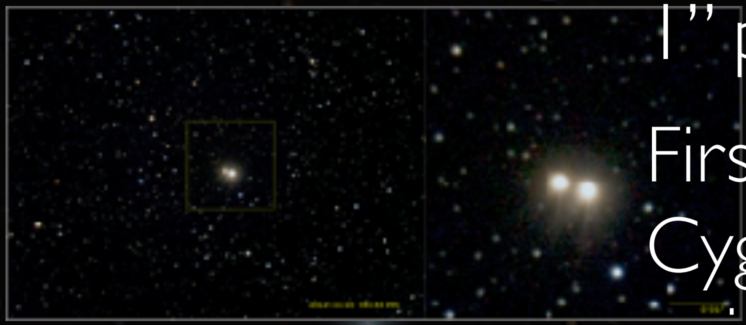
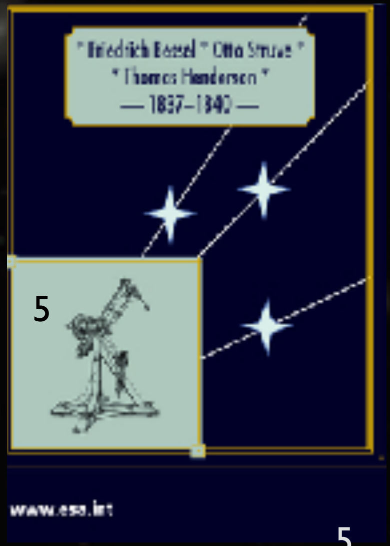
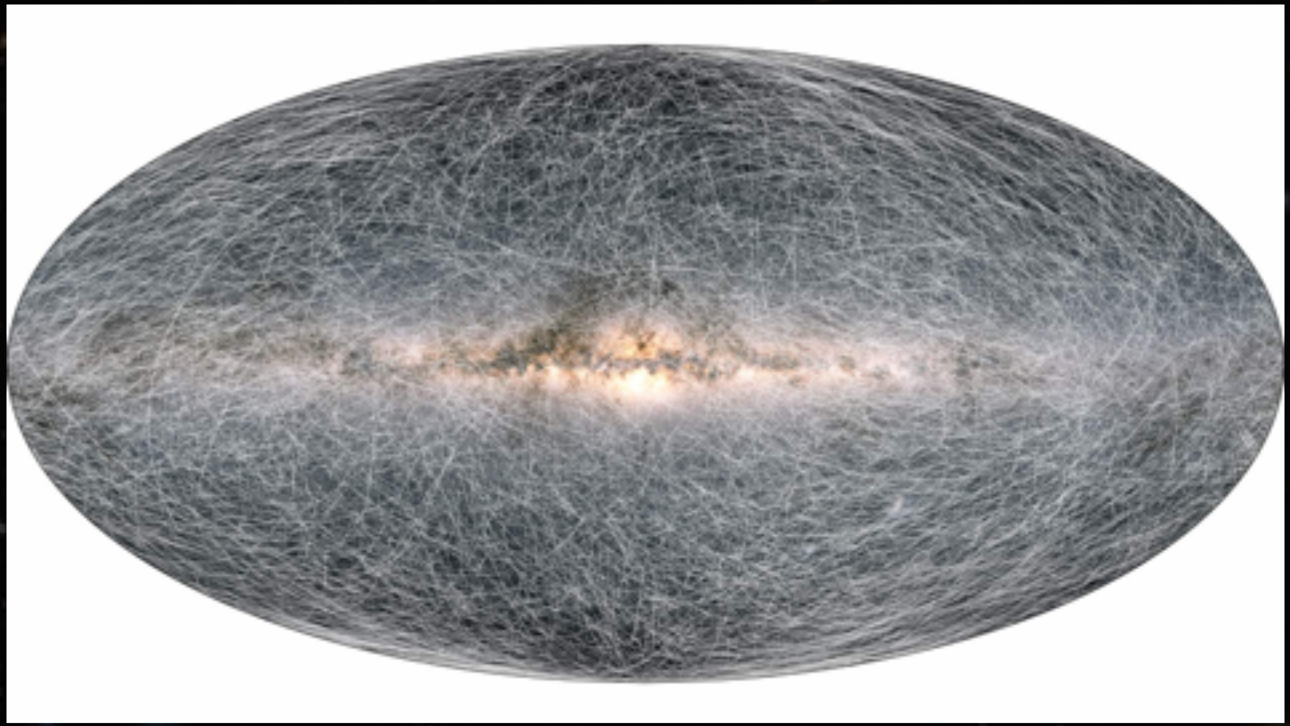


Friedrich Wilhelm Bessel: few stars measured to 1'' precision

First reliable measurement of parallax of 61 Cygni at10.4 light-years: revised the scale of the universe by ~ a million



Laboratories in the Sky: New Physics from the Stars



A billion stellar motions as precise as 10-100 *micro*-as, pinning down the history of the Milky Way and nearby cosmic distances

Discovery of supermassive black hole Sag A* and tests of GR

Today

Outline:

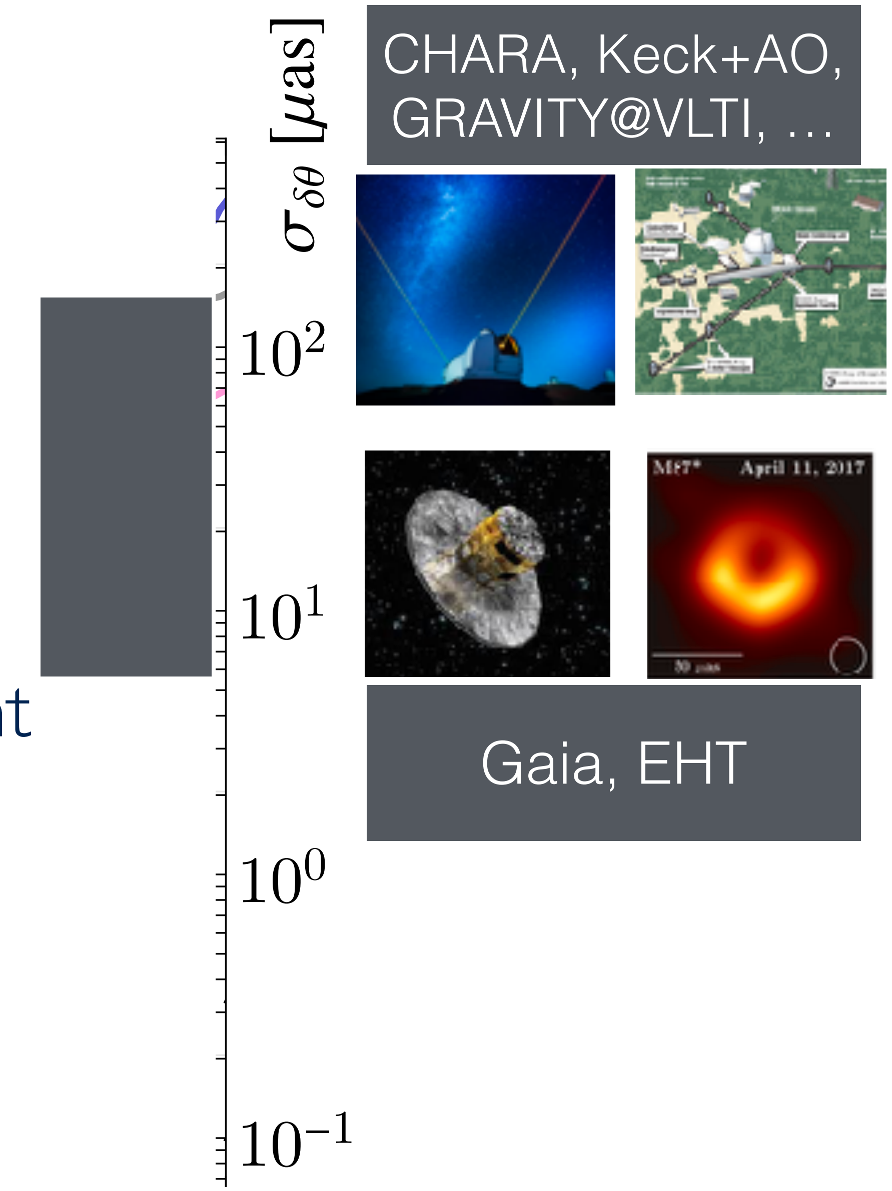
- Coherence in the sky: interfering intensities
- EPIC: extended path intensity correlation
- Measurements with precision relative astrometry

Intensity Interferometry Science Reach

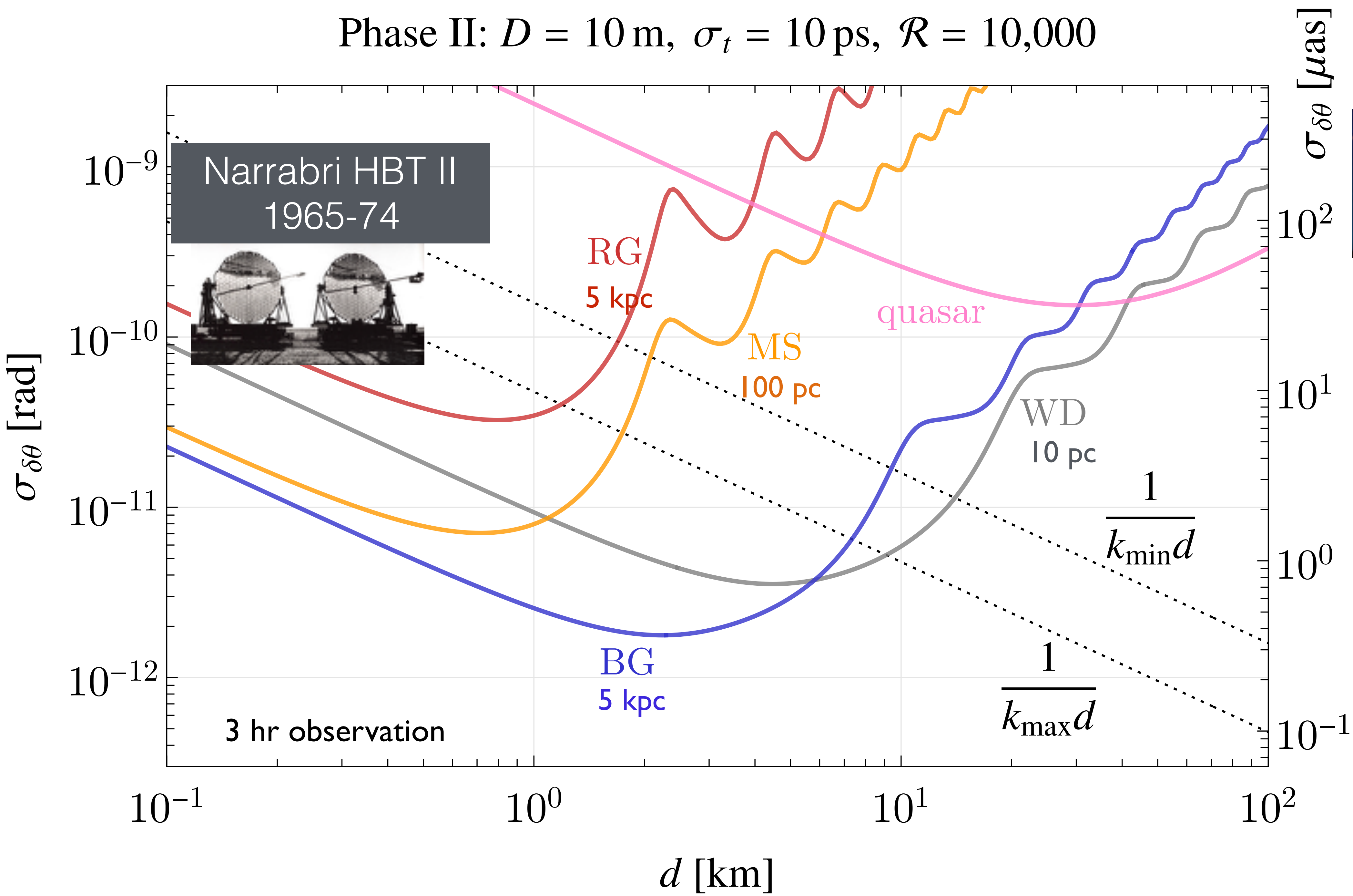
$$\sigma_{\theta_{\rm res}} \sim \frac{\lambda}{d} \approx 10^{-6}\,{\rm rad} \approx 0.4\ {\rm arcsec}$$

$$\sigma_{\delta\theta} \simeq \max\{\frac{\sigma_{\theta_{res}}}{\rm SNR}, \sigma_{\theta_{noise}}\}$$

How do we push the precision beyond the current techniques?



Intensity Interferometry Science Reach



$$\sigma_{\theta_{\text{res}}} \sim \frac{\lambda}{d} \sim \underbrace{10^{-12}\,\text{rad}}_{0.2\,\mu\text{as}} \left(\frac{\lambda}{500\,\text{nm}}\right)\left(\frac{100\,\text{km}}{d}\right)$$

$$\sigma_{\delta\theta} \simeq \frac{1}{\text{SNR}}\sigma_{\theta_{\text{res}}}$$

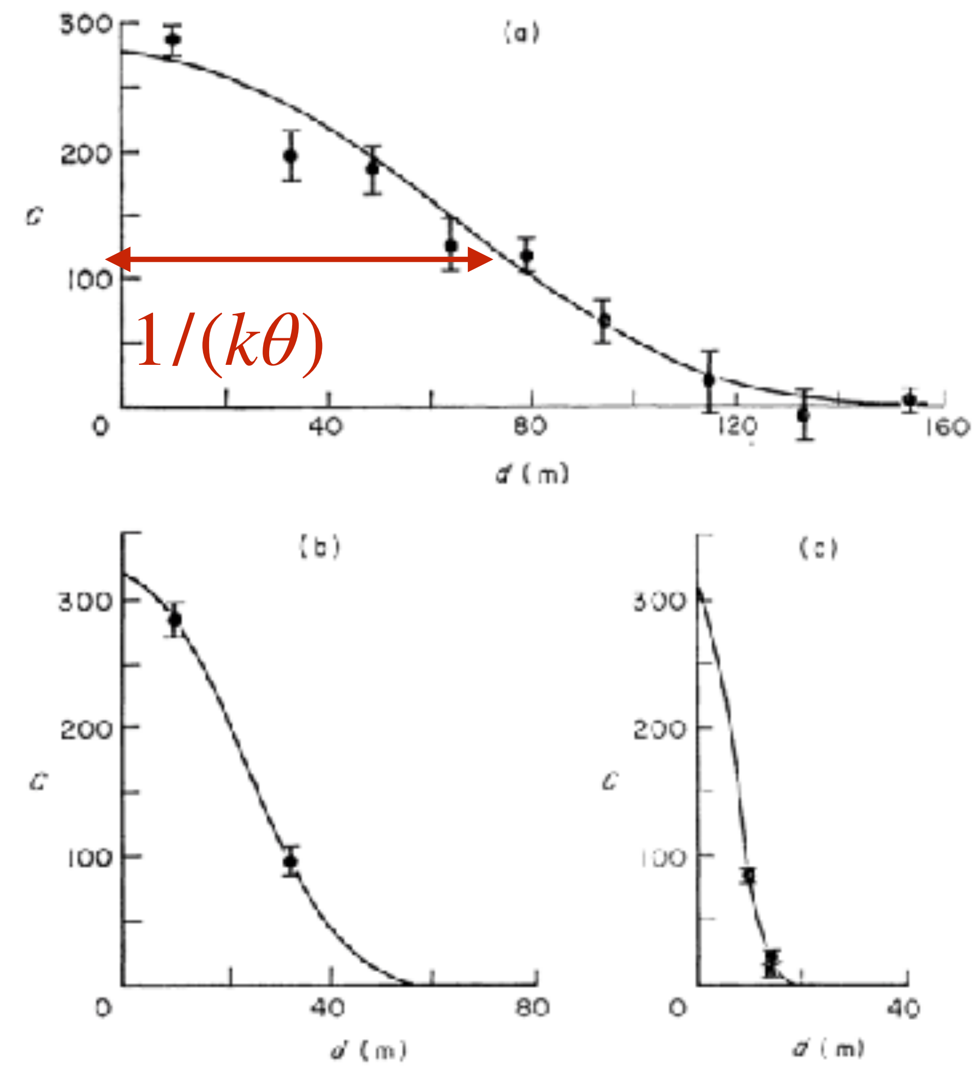
[Marios Galanis, Ken Van Tilburg, **MB**, Neal Weiner, 2307.03221]

Intensity Interferometry

Record photon counts, not electric fields: no need to physically recombine light

Resolution set by telescope separation: can be 10 m to 1000 km

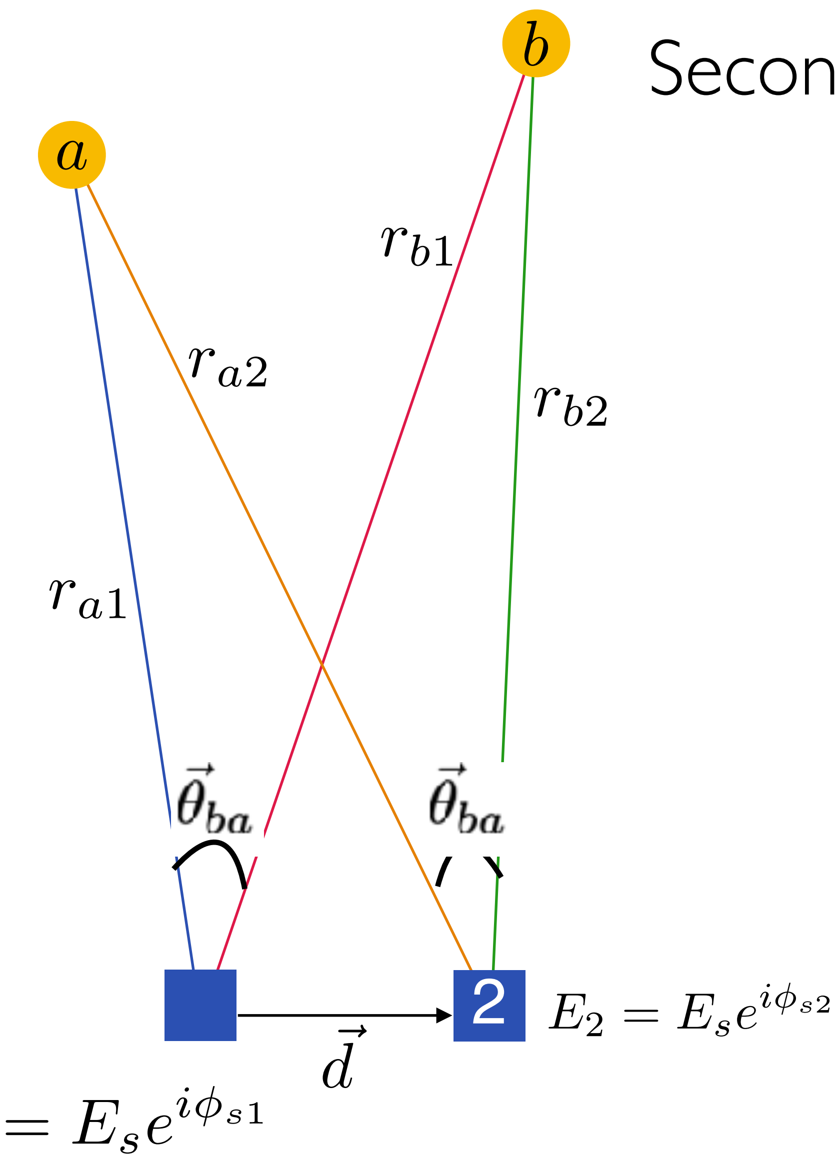

Hanburry Brown and Twiss, 1965-74



HBT made some of the most precise measurements of stellar diameters, comparable to modern optical interferometers, EHT resolution, end of mission Gaia centroiding precision

Intensity Interferometry

Second Order Correlations of Light



$$\phi_{sj}(t) = -\omega t + k r_{sj} + \phi_s^{\rm em}(t - r_{sj})$$

Classical wave interference:

$$C \equiv \frac{\langle I_1(t) I_2(t+\tau)\rangle}{\langle I_1\rangle \langle I_2\rangle} - 1$$

$$= \frac{\langle E_1(t) E_1^*(t) E_2(t+\tau) E_2^*(t+\tau)\rangle}{\langle E_1 E_1^*\rangle \langle E_2 E_2^*\rangle} - 1$$

$$\simeq \frac{1}{\sqrt{2}\sigma_k \sigma_t} \cos\left[k(r_{a1} + r_{b2} - r_{a2} - r_{b1})\right]$$

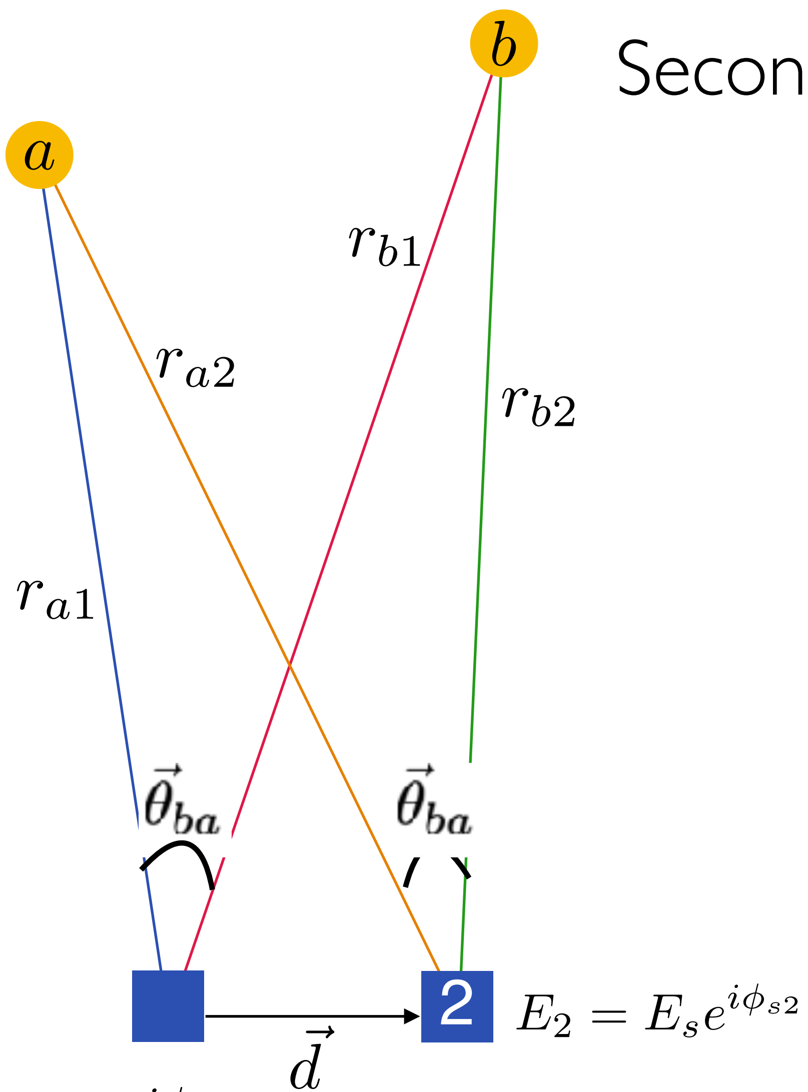
$$\simeq \frac{1}{\sqrt{2}\sigma_k \sigma_t} \cos\left[k\vec{d}\cdot\vec{\theta}_{ba}\right]$$

Crossed paths longer by a relative phase $k\vec{d}\cdot\vec{\theta}_{ba}$

[Hanburry-Brown & Twiss '54,'56; Purcell '56]

Intensity Interferometry

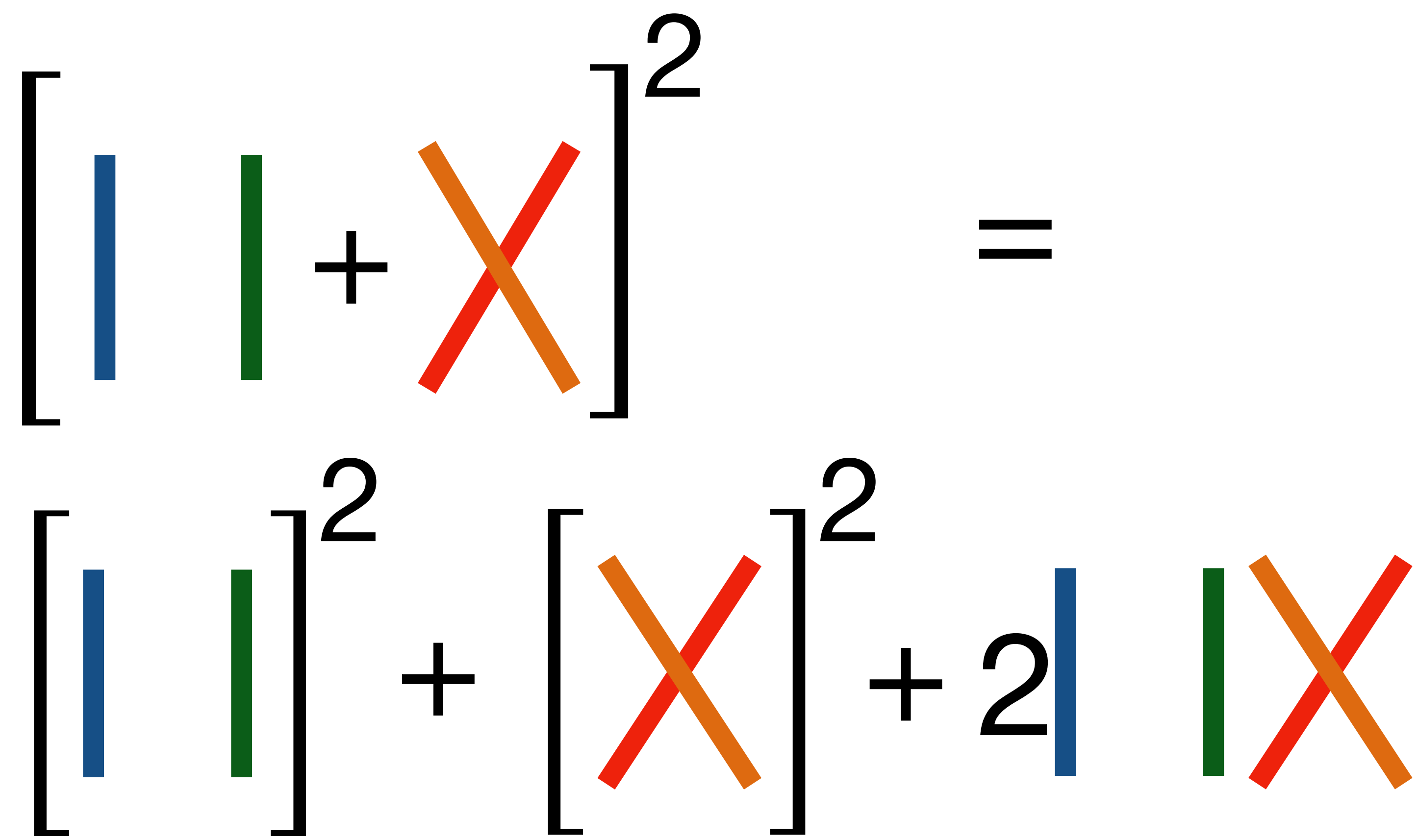
Second Order Correlations of Light



$$E_1 = E_s e^{i\phi_{s1}}$$

$$\phi_{sj}(t) = -\omega t + k r_{sj} + \phi_s^{\mathrm{em}}(t - r_{sj})$$

Quantum mechanical constructive interference:



Crossed paths longer by a relative phase $k\vec{d} \cdot \vec{\theta}_{ba}$

Edward Purcell

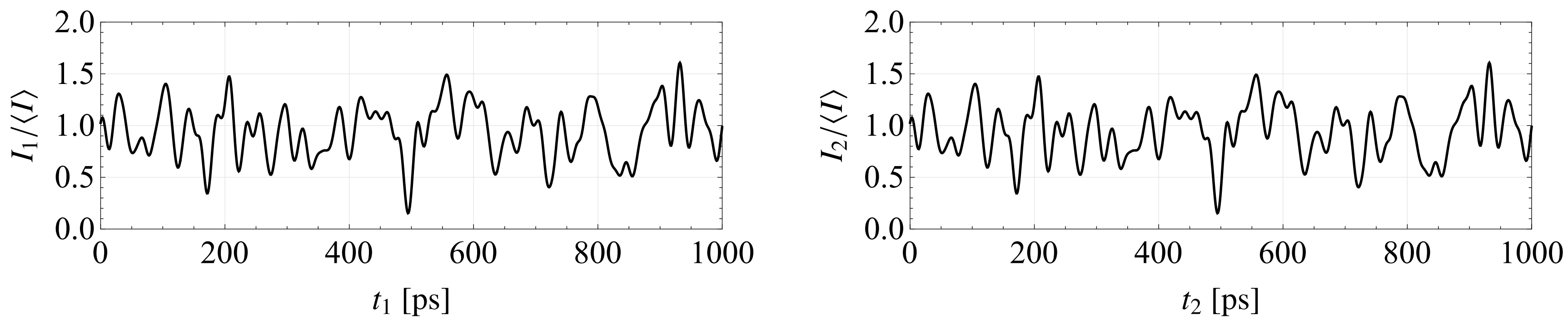
"The Brown-Twiss effect, far from requiring a revision of quantum mechanics, is an instructive illustration of its elementary principles."

-- Nature 178 (1956)

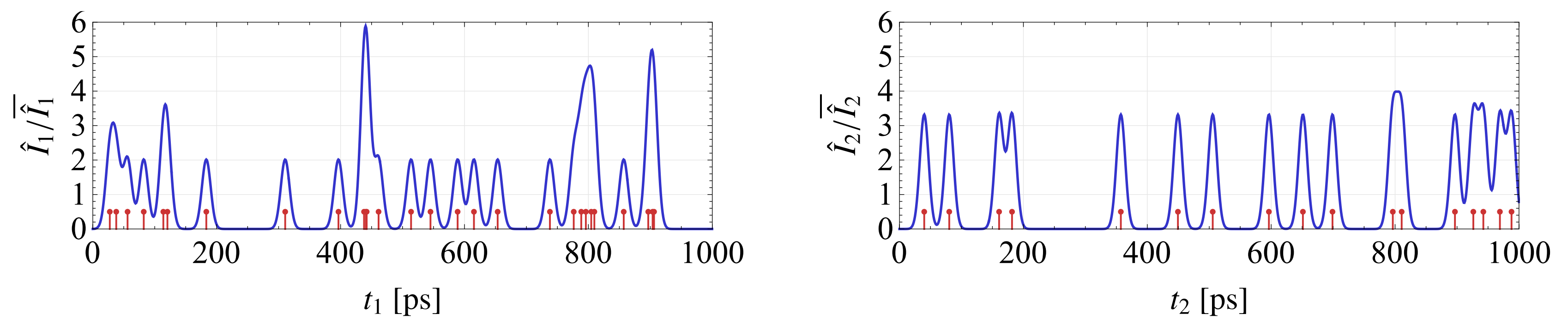
[Hanburry-Brown & Twiss '54,'56; Purcell '56]

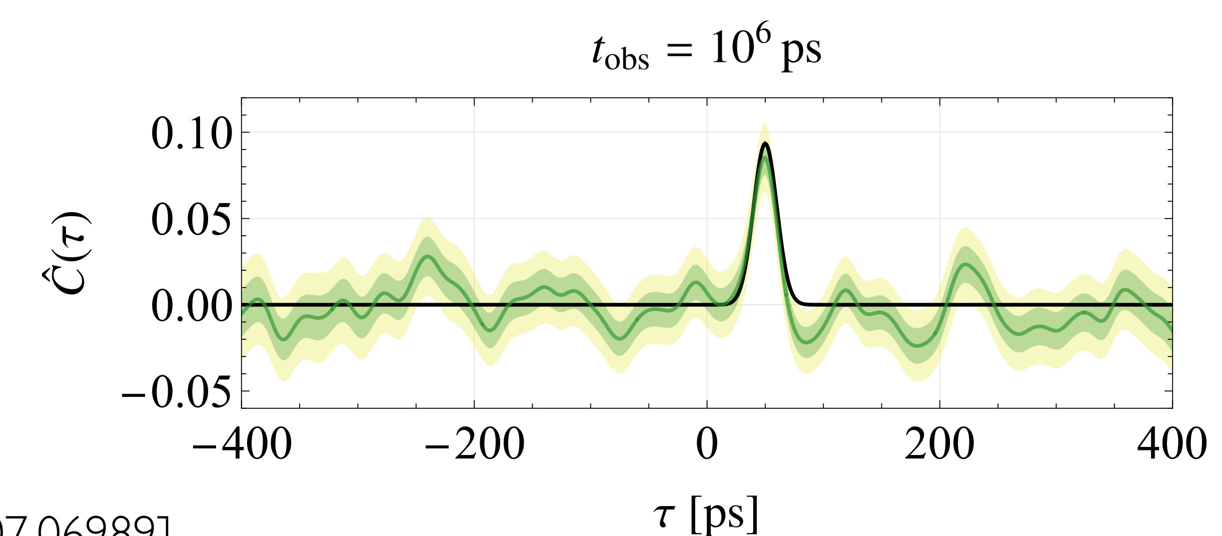
Intensity Interferometry

Random fluctuations in intensities



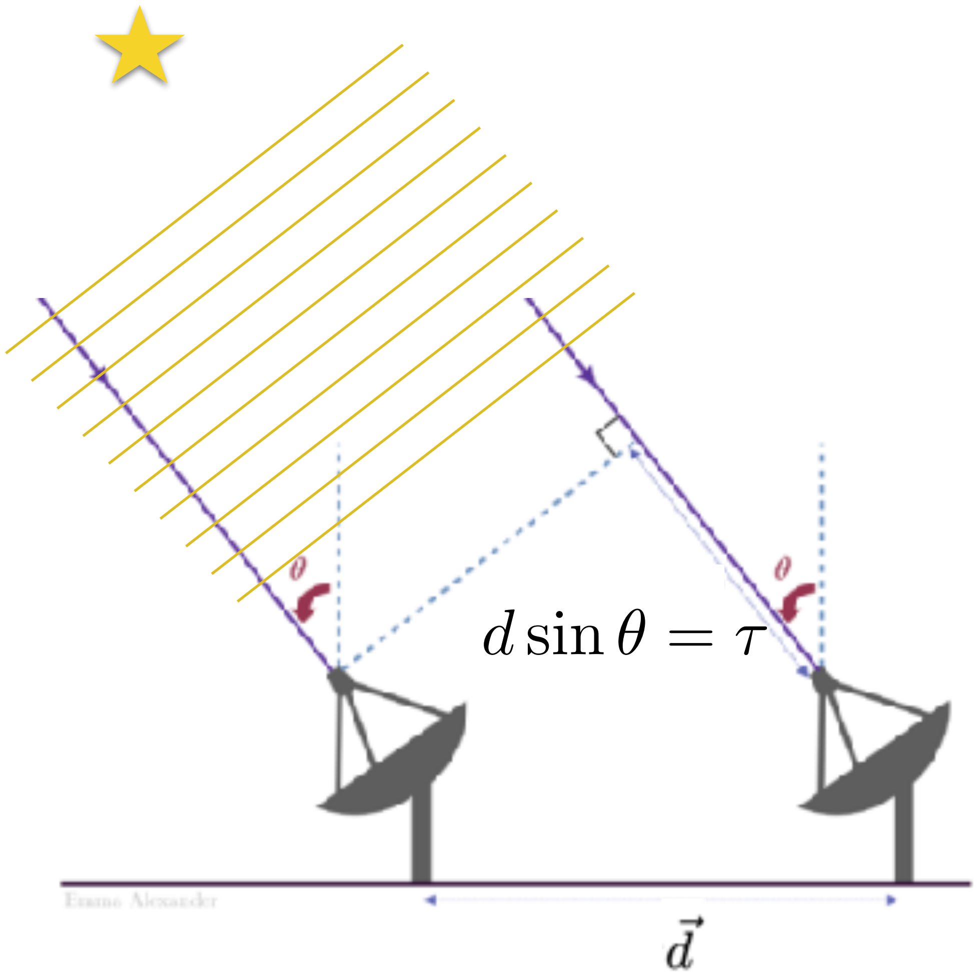
Result in correlations in photon counts





[Galanis, Van Tilburg, **MB**, Weiner, 2307.06989]

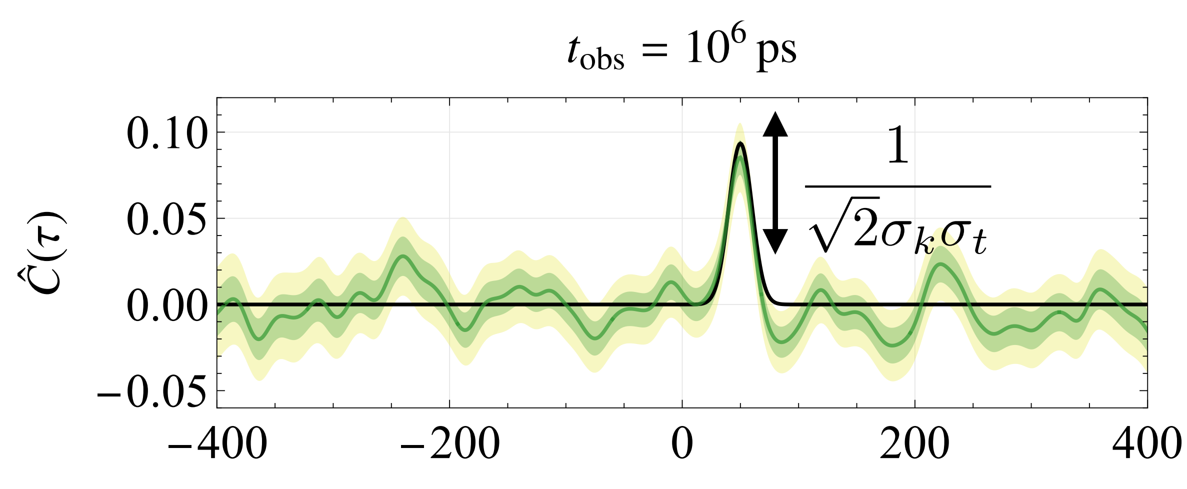
Intensity Interferometry



Need fast enough photon counter to prevent averaging over too many independent coherence times of the radiation

$$C = \frac{\langle I_1(t) I_2(t+\tau)\rangle}{\langle I_1\rangle \langle I_2\rangle} - 1 \simeq \frac{1}{\sqrt{2}\sigma_k\sigma_t}\,|\mathcal{V}|^2$$

$$|\mathcal{V}|^2 \propto \left|\text{Fourier transform at angular wavenumber } k\vec{d}\right|^2$$



[Galanis, Van Tilburg, **MB**, Weiner, 2307.06989]

Outline:

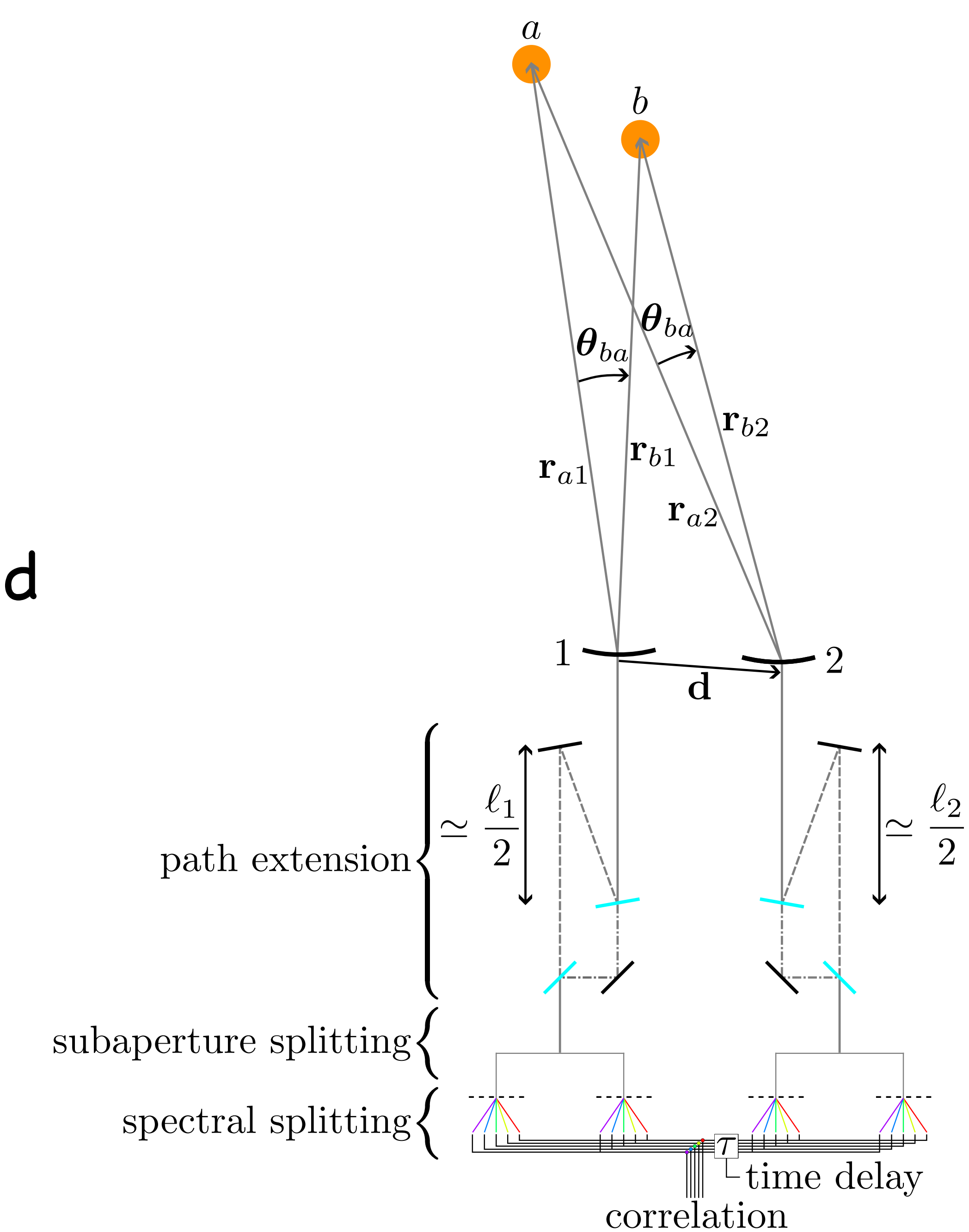
- Coherence in the sky: interfering intensities
- EPIC: extended path intensity correlation
- Measurements with precision relative astrometry

Extended Path Intensity Correlation

Increase field of view of intensity interferometry

Measure motion of bright, closely separated sources to unprecedented precision

Robust to atmospheric and telescope distortions



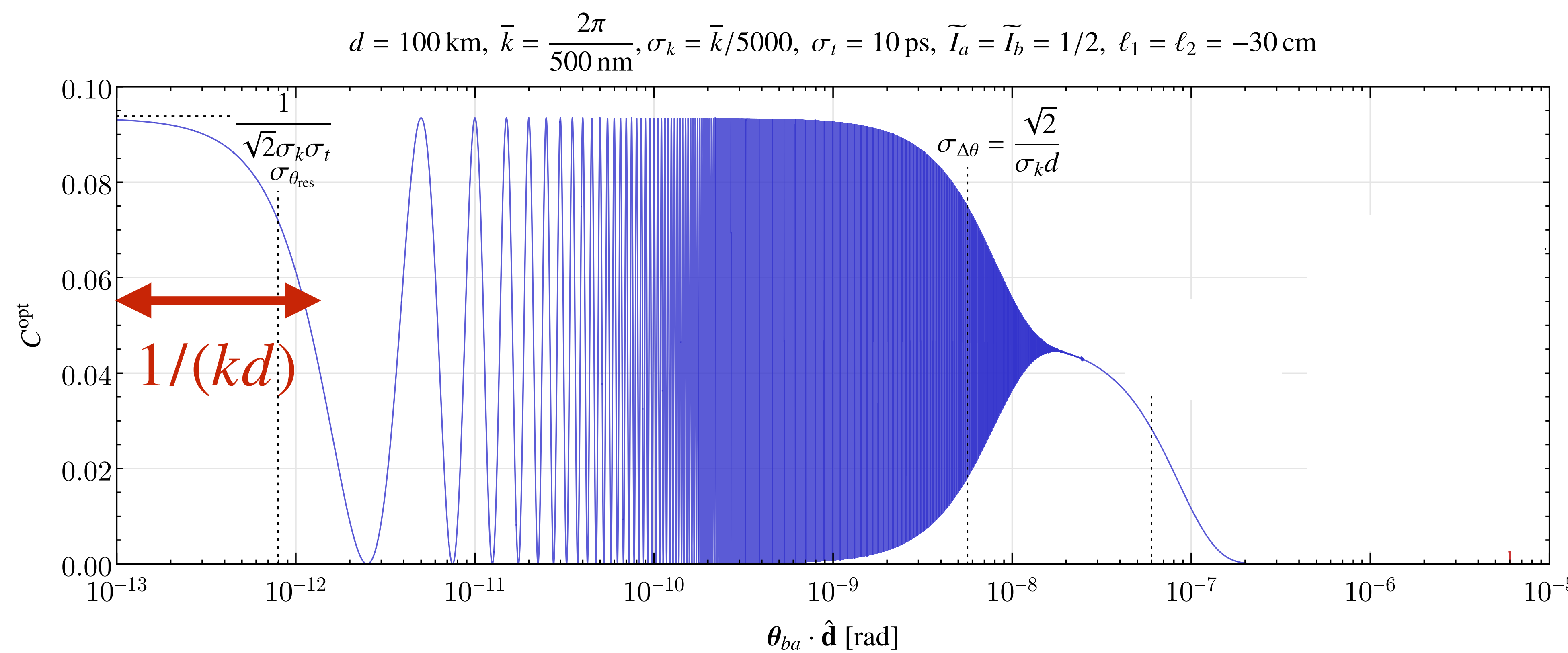
[Van Tilburg, **MB**, Galanis, Weiner, 2307.03221]
[Galanis, Van Tilburg, **MB**, Weiner, 2307.06989]

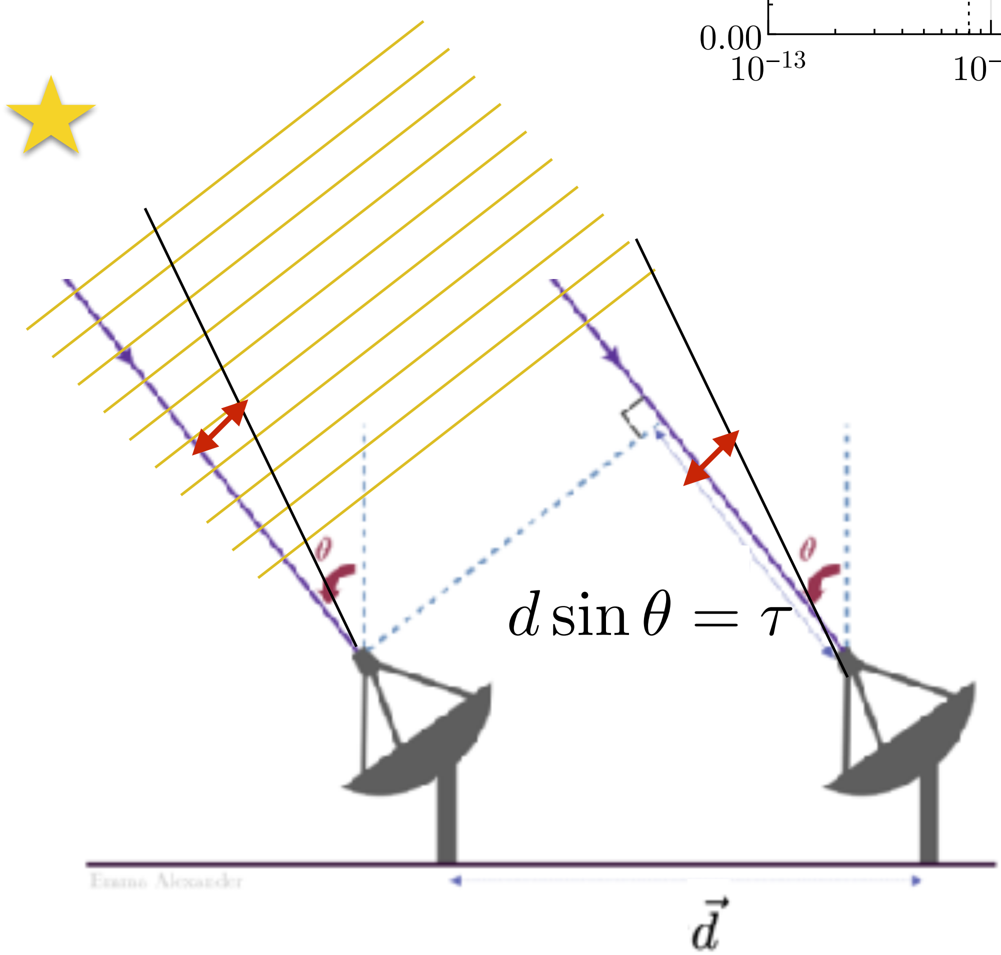
Ken Van Tilburg

Marios Galanis

Neal Weiner

Overcoming Limitations: Tiny Field of View

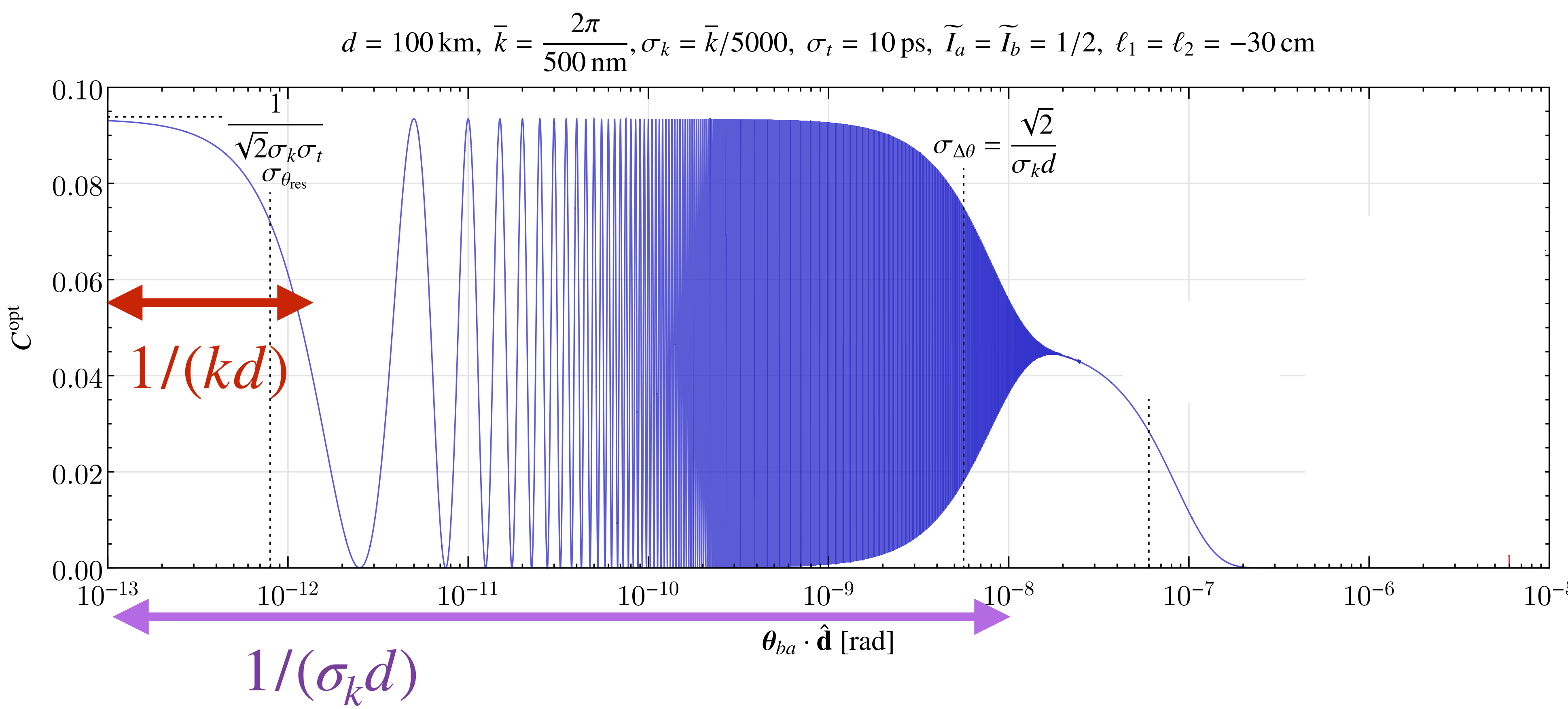


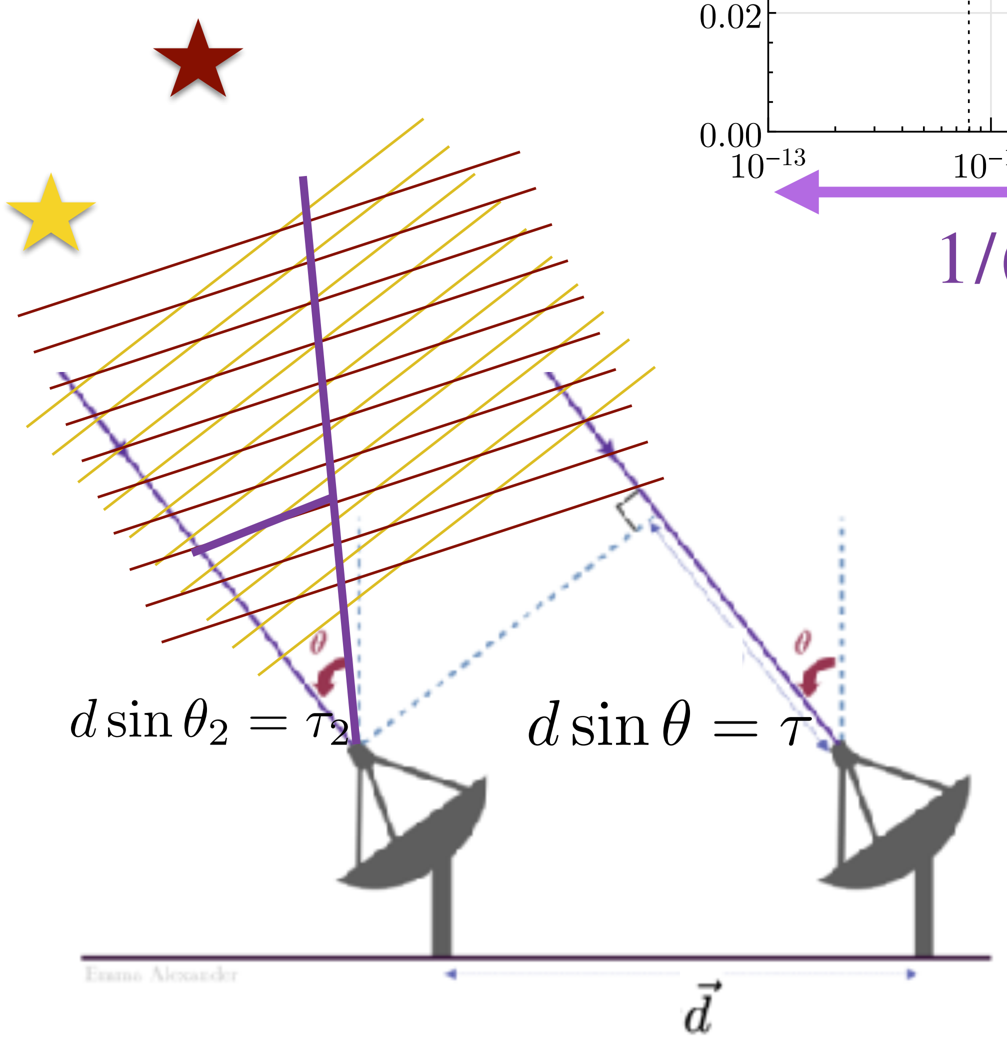


$$C = \frac{\langle I_1(t) I_2(t+\tau)\rangle}{\langle I_1\rangle \langle I_2\rangle} - 1$$

$$= \frac{1}{\sigma_k \sigma_t} \cos(k\mathbf{d}\cdot\boldsymbol{\theta}_{ab})\,\mathrm{ex}$$

Overcoming Limitations: Tiny Field of View



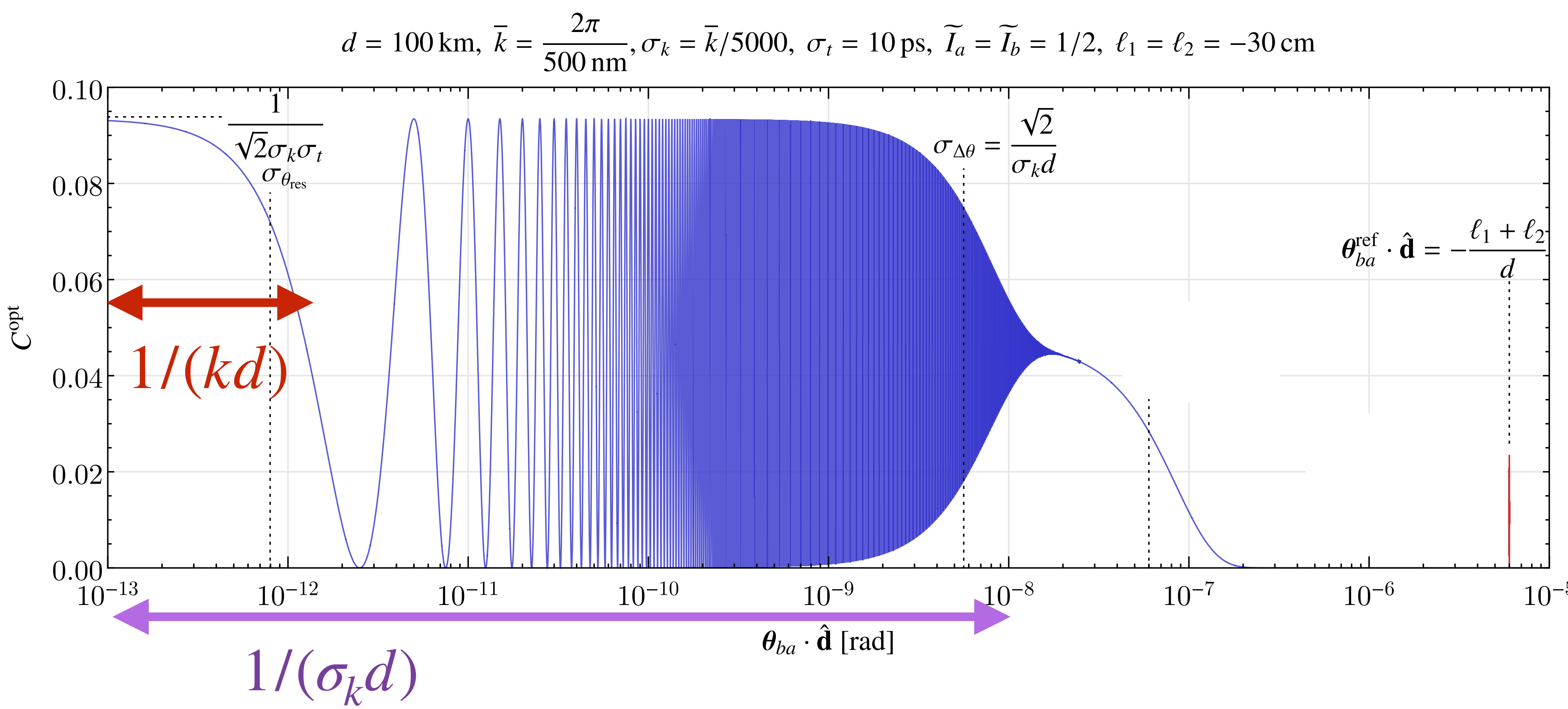


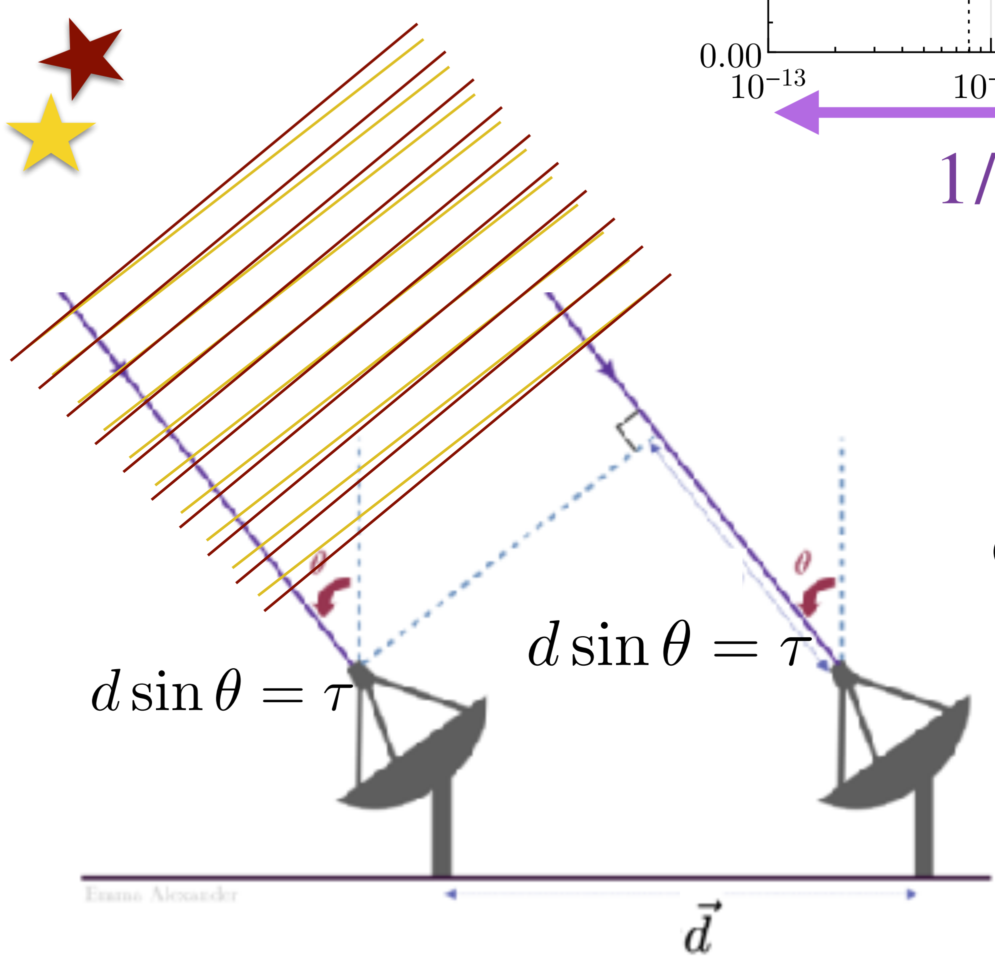
$$C = \frac{\langle I_1(t) I_2(t+\tau)\rangle}{\langle I_1\rangle \langle I_2\rangle} - 1$$

$$= \frac{1}{\sigma_k \sigma_t} \cos(k\mathbf{d}\cdot\boldsymbol{\theta}_{ab}) \exp\left[-\frac{(\sigma_k \mathbf{d}\cdot\boldsymbol{\theta}_{ab})^2}{4}\right]$$

Oscillatory term characteristic of the angular separation $1/(kd)$ of the two stars, modulated by a broader Gaussian of the spectral width $1/(\sigma_k d)$

Overcoming Limitations: Extended Path



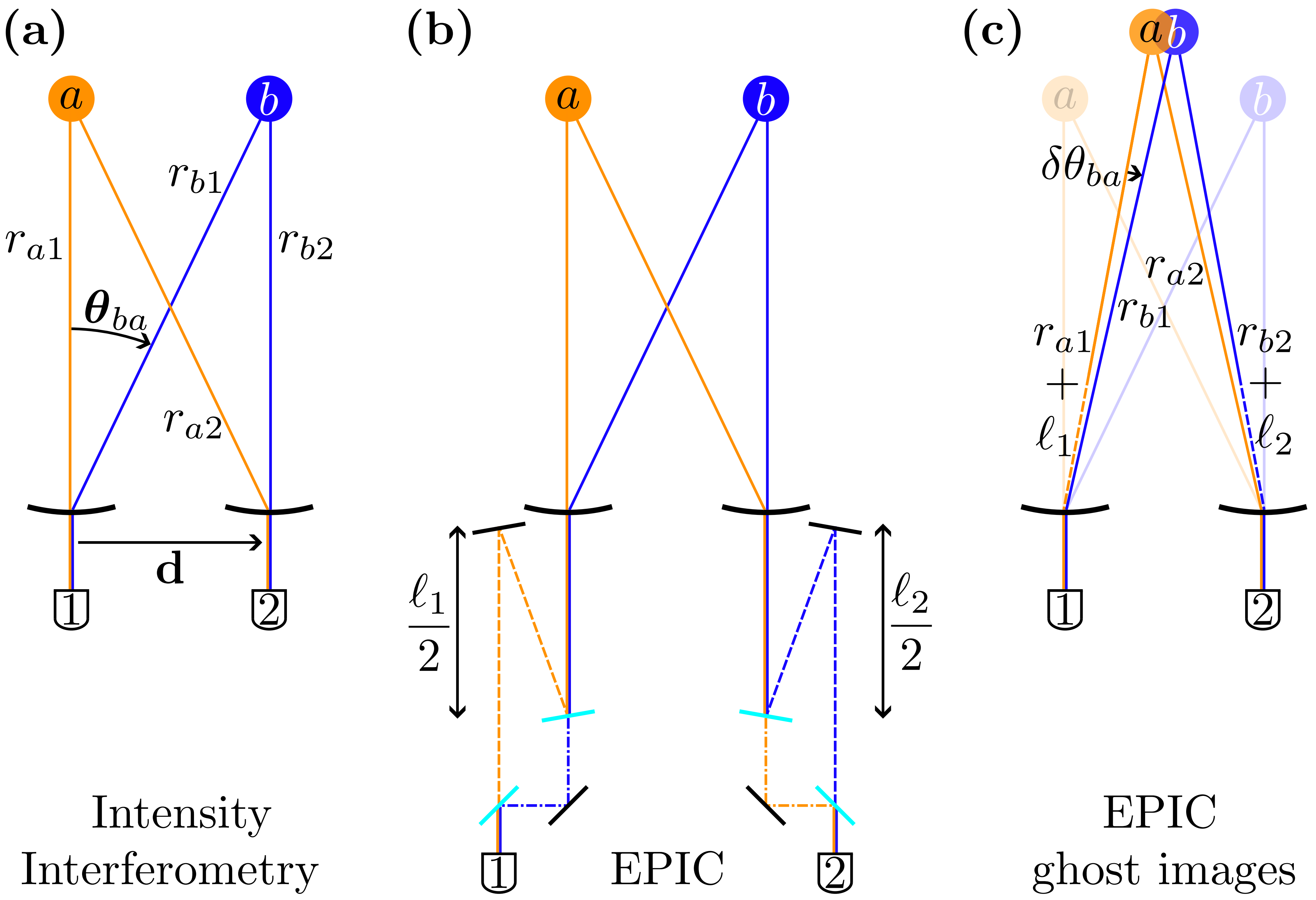


$$C = \frac{\langle I_1(t) I_2(t+\tau)\rangle}{\langle I_1\rangle \langle I_2\rangle} - 1$$

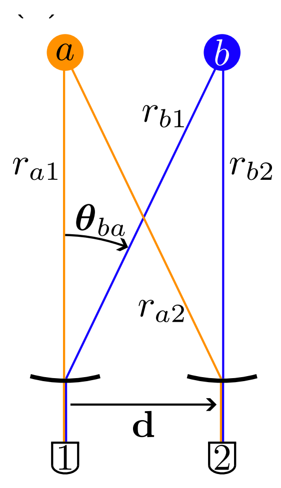
$$\propto \cos[k(\mathbf{d}\cdot\boldsymbol{\theta}_{ab} - 2\ell)] \exp\left\{-\frac{[\sigma_k(\mathbf{d}\cdot\boldsymbol{\theta}_{ab} - 2\ell)]^2}{4}\right\}$$

Simply add an optical path extension!

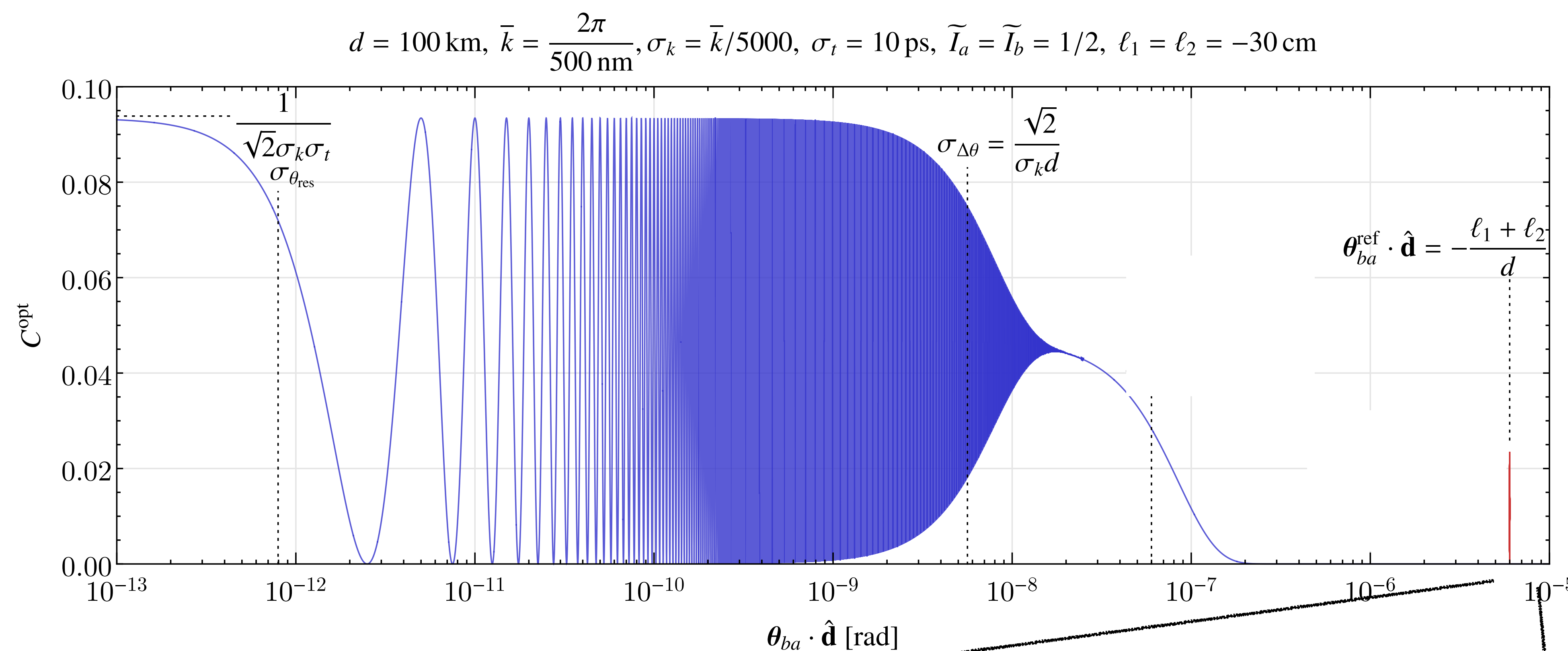
Overcoming Limitations: Extended Path

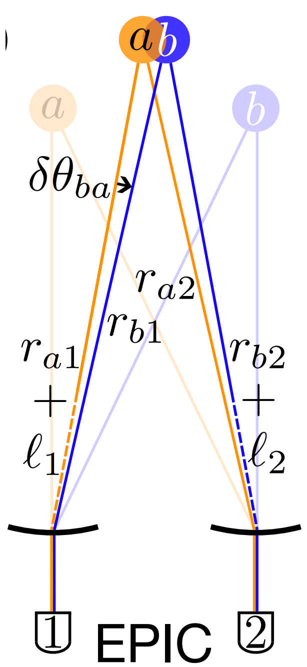


Overcoming Limitations: Extended Path

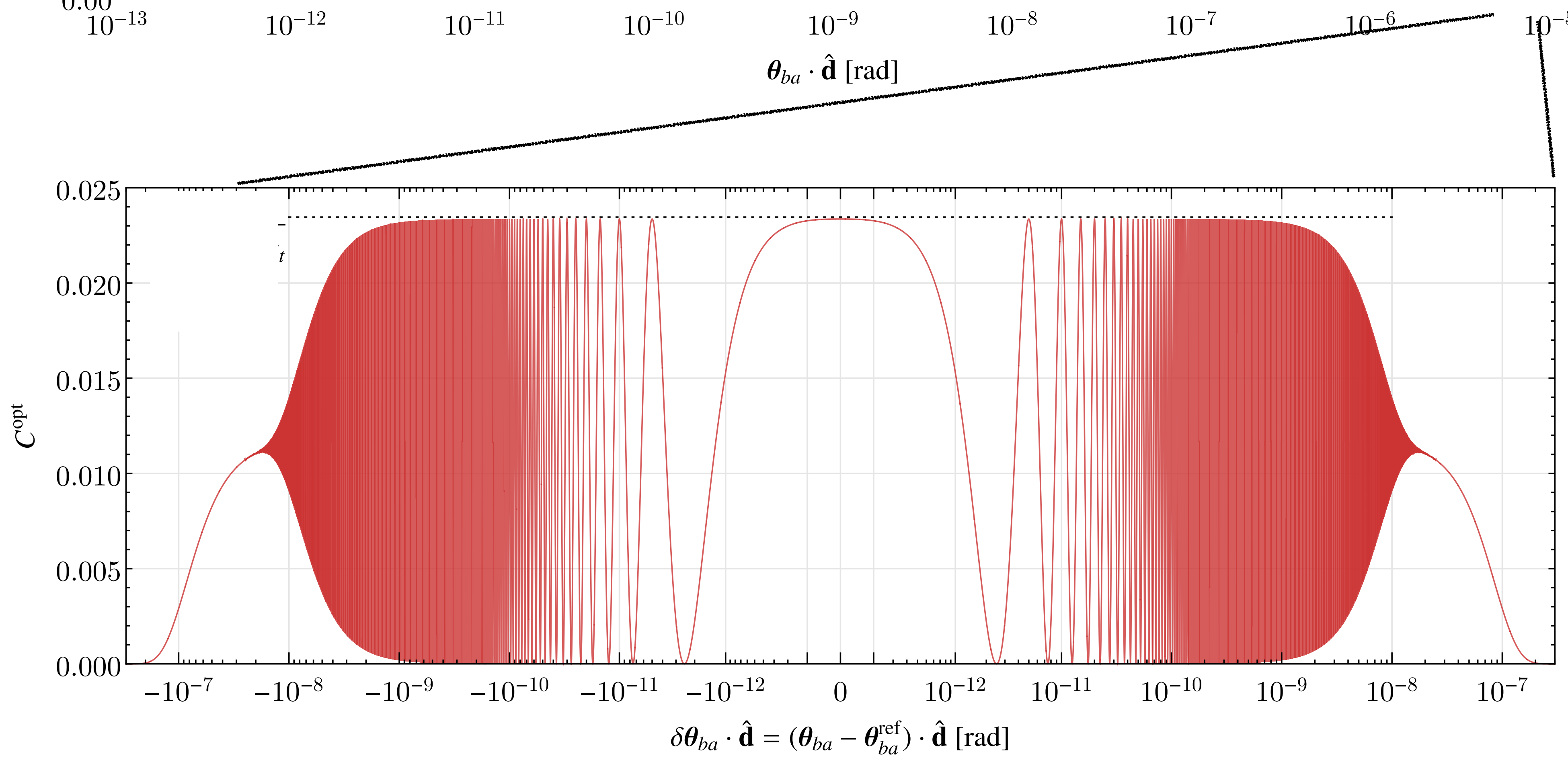


Intensity Interferometry



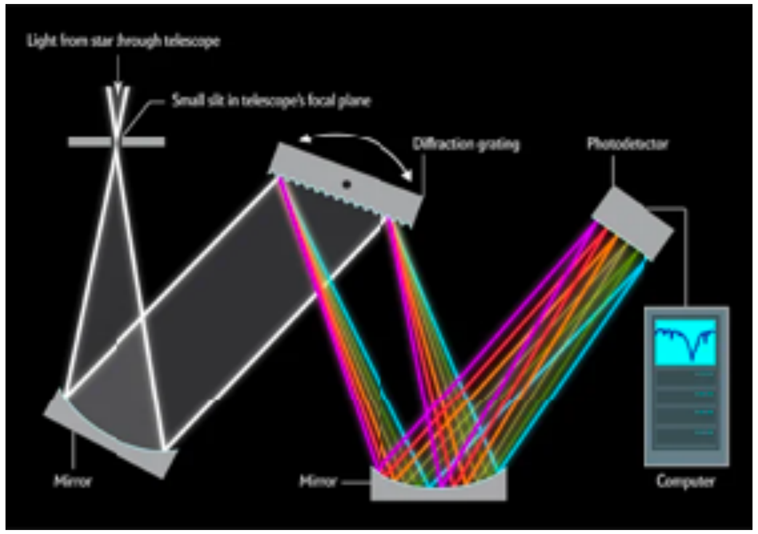


EPIC ghost images



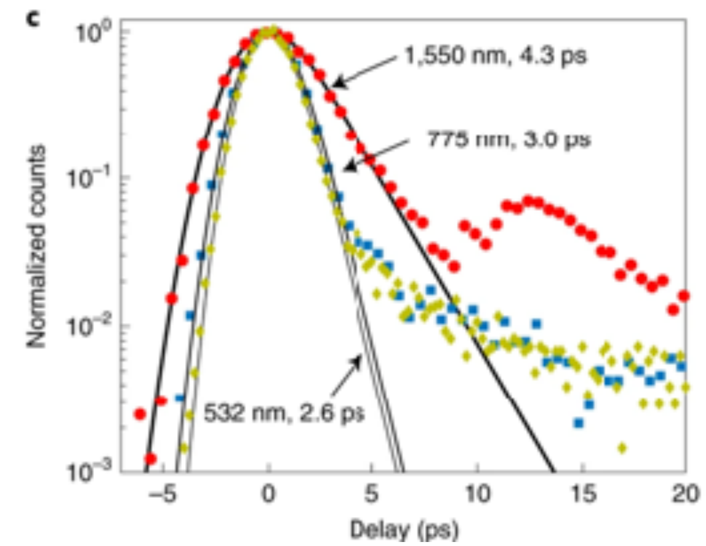
Overcoming Limitations: Signal to Noise Ratio

Technological advances allow for fainter sources:



Multi-Channel Spectroscopy

Kim, Jae-Young et al. (2014) JKAS.2014.47.6.235.



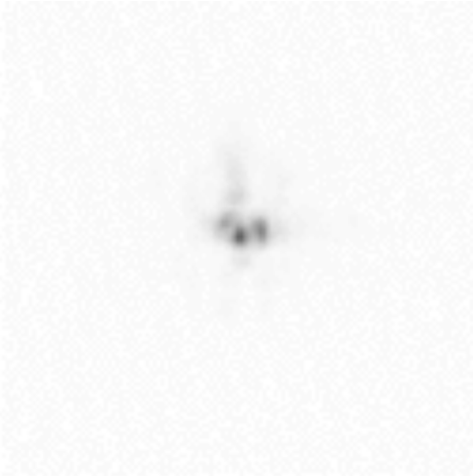
Ultra-Fast Single-Photon Detection

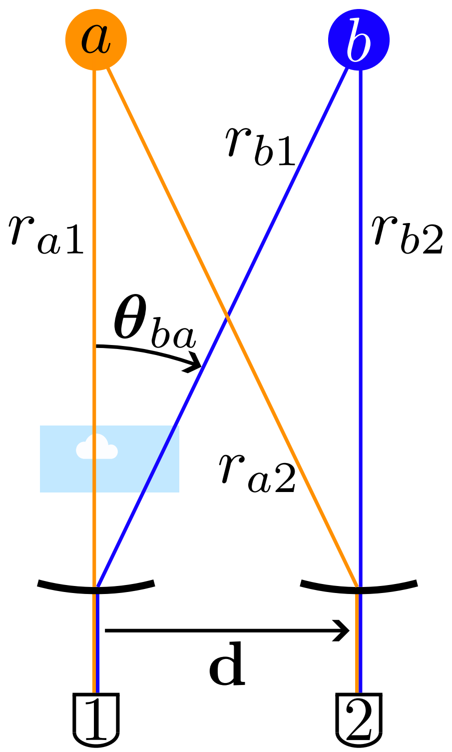
Korzh, B., Zhao, QY., Allmaras, J.P. et al. Nat. Photonics 14, 250–255 (2020)

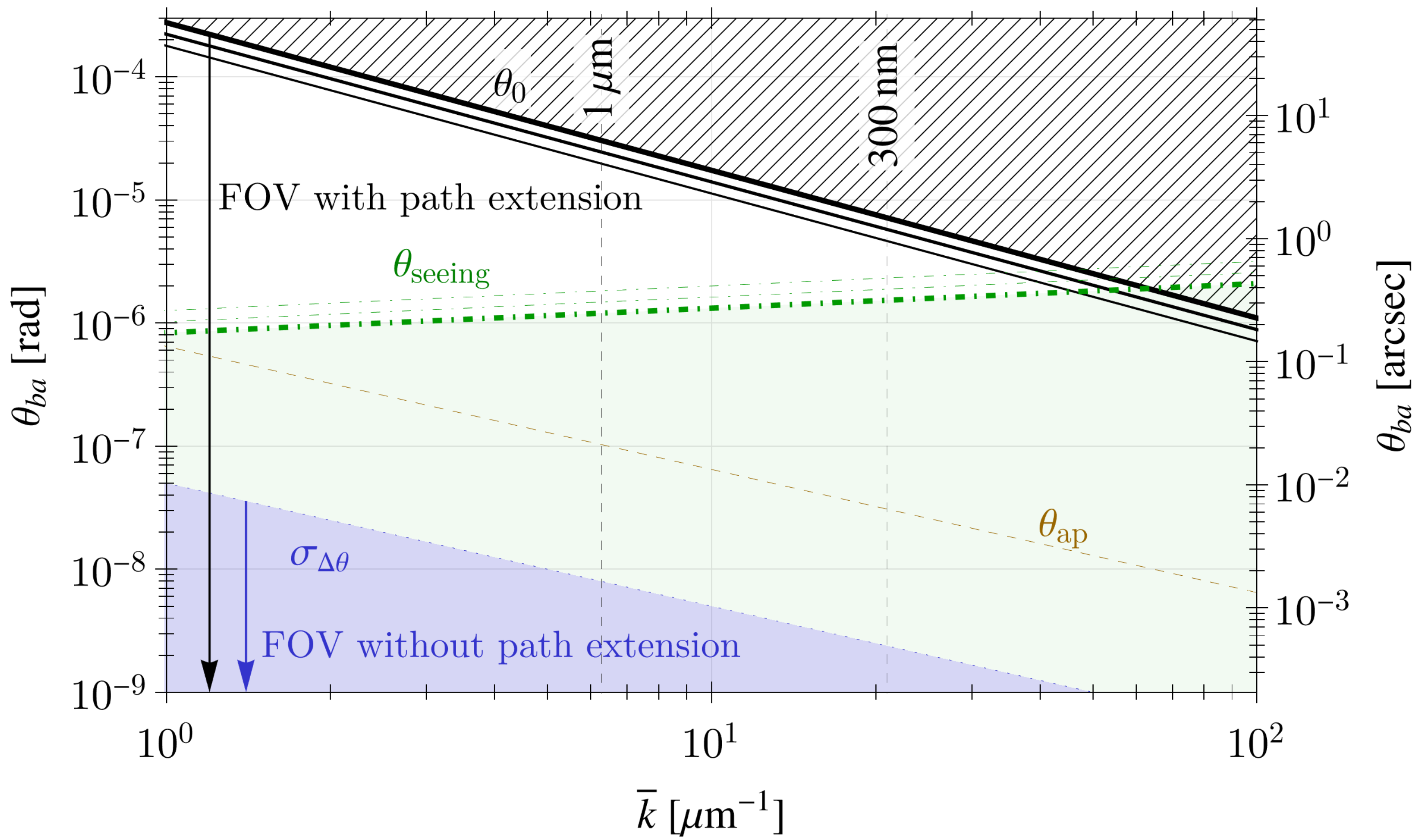
U. Abeysekara et al., Nature Astronomy 4, 1164 (2020)
L. Zampieri et al MNRAS 506, 1585 (2021)

Large Collecting Areas

Atmospheric Effects







Seeing angle:

scale of turbulent fluctuations

Limits resolution of ground based telescopes

isoplanatic patch angle

Scale on which turbulent fluctuations are correlated

Limits effective field of view (also for adaptive optics systems)

Outline:

- Coherence in the sky: interfering intensities
- EPIC: extended path intensity correlation
- **Measurements with precision relative astrometry**

"Let us then consider some of the immediate programmes which a more sensitive intensity interferometer might tackle, ***bearing in mind that the most important results of research may well prove to be those which one cannot foresee."***

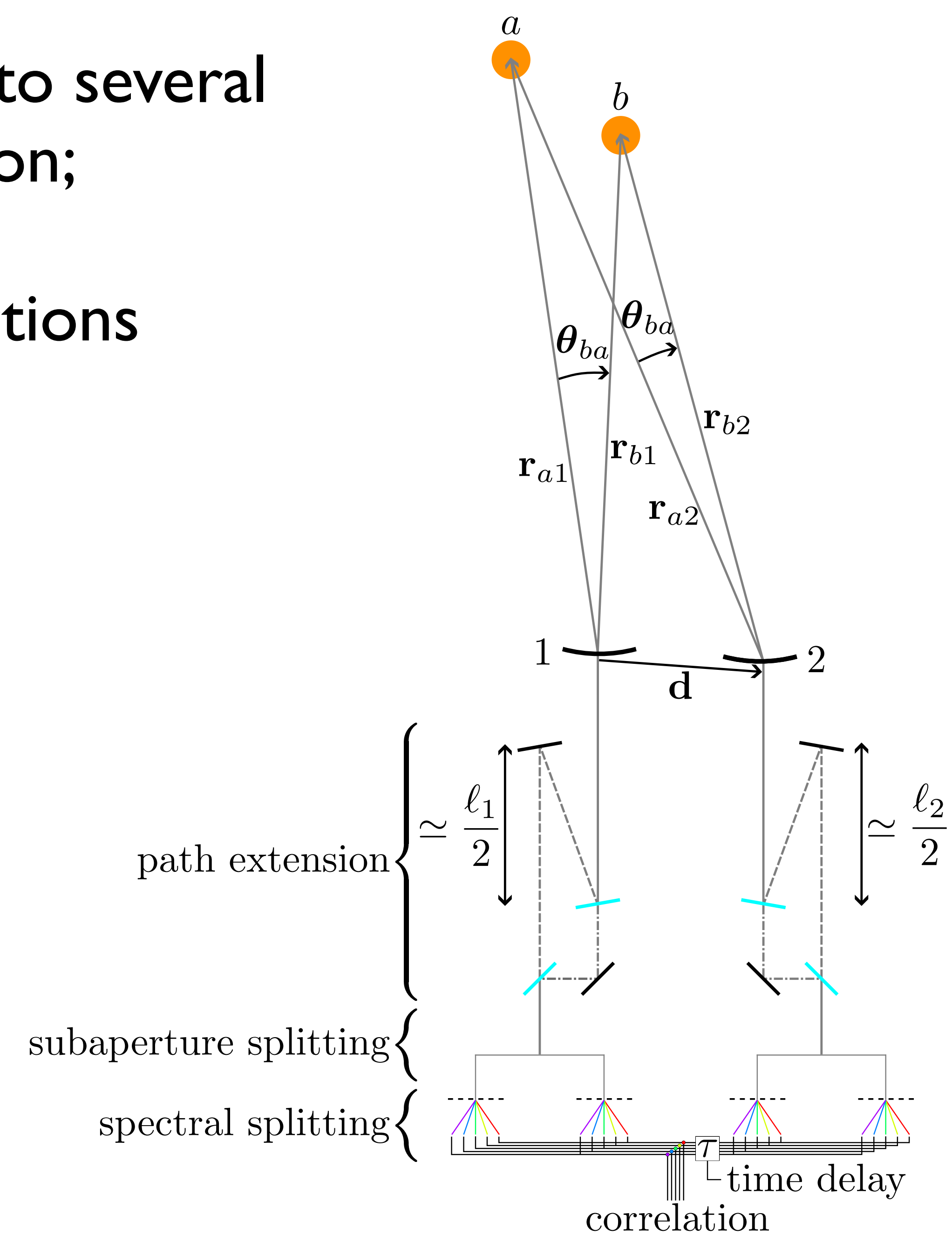
— Hanbury Brown, 1974

Intensity Interferometry Science Reach

Measure motion of bright, closely separated (up to several arcsec) sources to unprecedented precision;

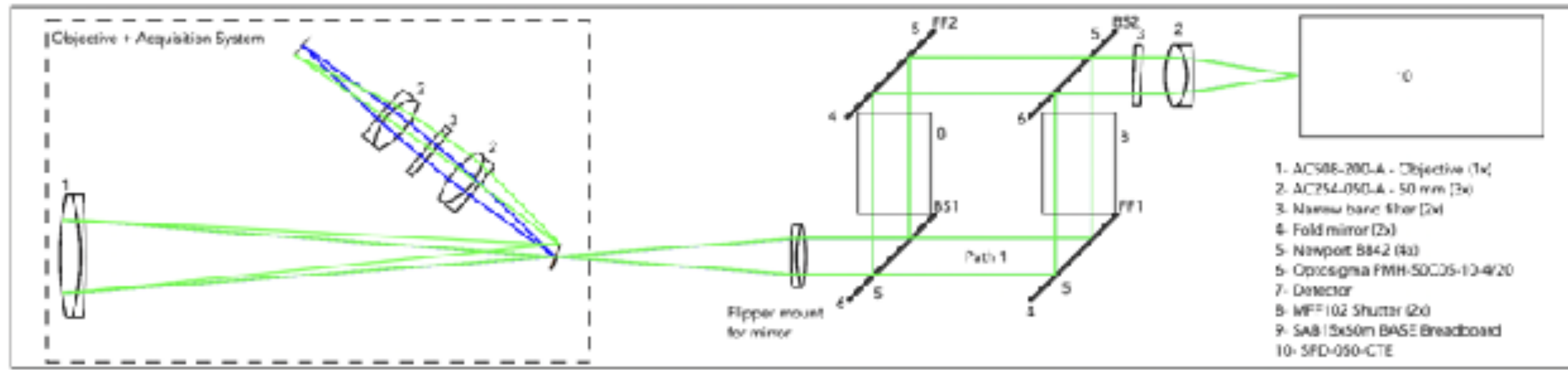
Robust to atmospheric and telescope distortions

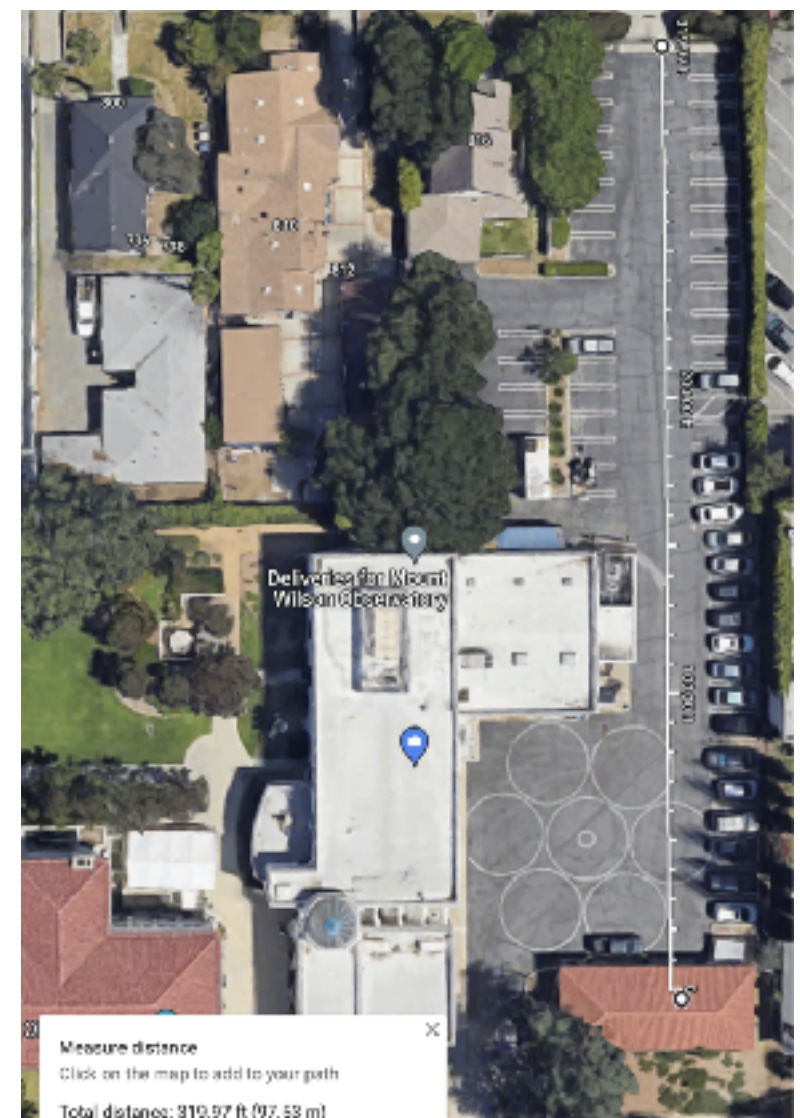
- Exoplanet detection
- Binary orbit characterization
- Stellar and black hole microlensing
- Galactic accelerations
- Spin and quadrupole moments of the central Milky Way black hole
- …



From paper to parking lot… to telescopes?

Nick Konidaris
Carnegie Observatories





Test bed for detector, optics and timing setup

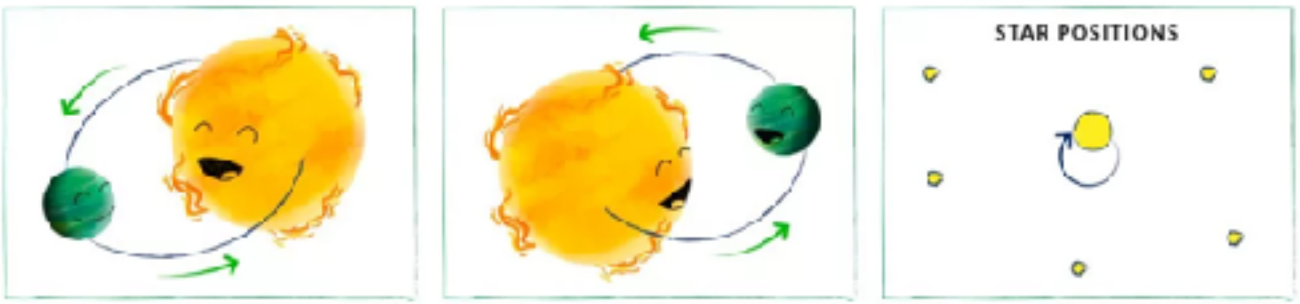
Set the stage for a telescope prototype

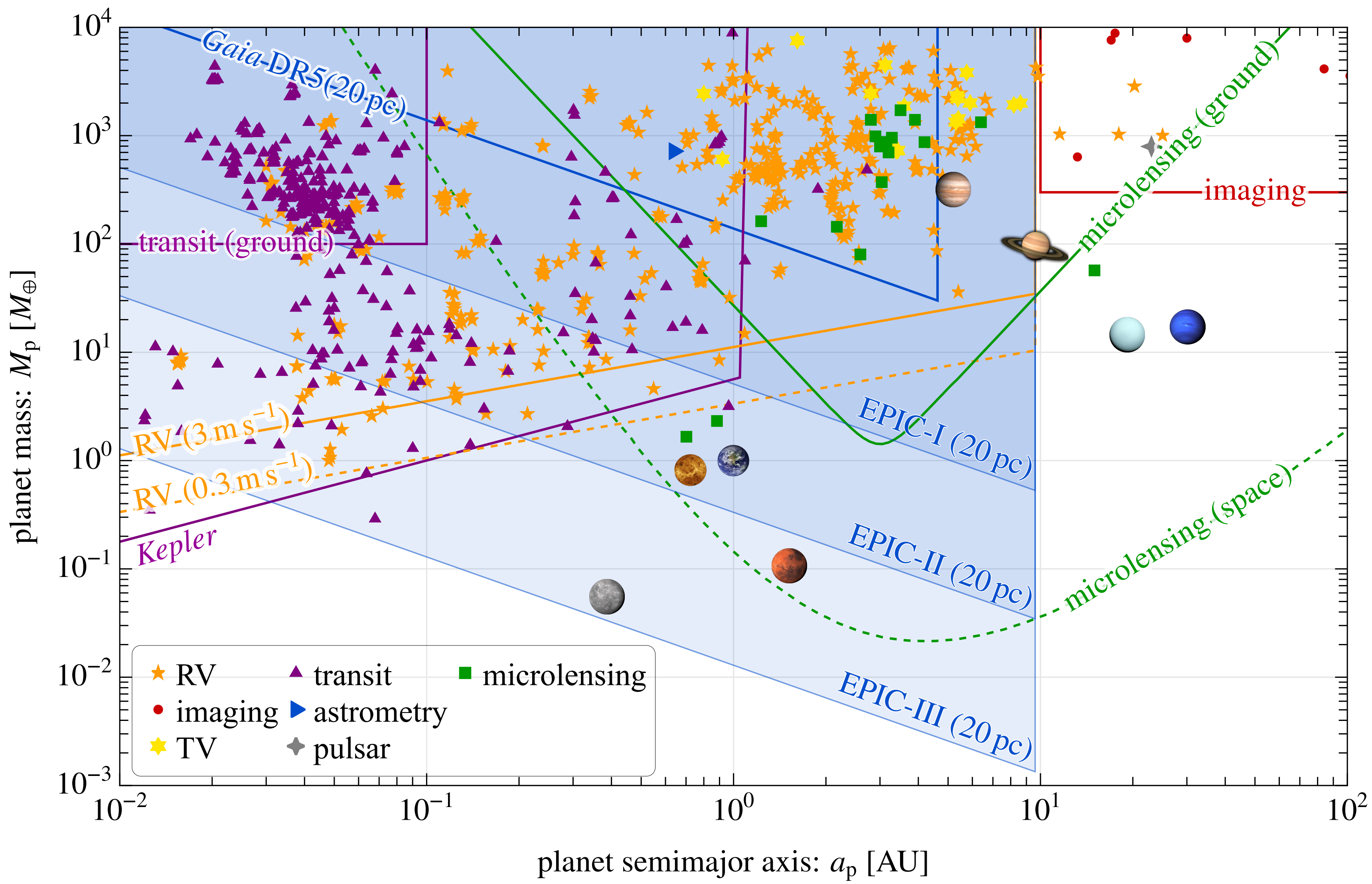
Benchmark parameters for science cases:

Phase	D	σ_t	$\mathcal{R}$	n_{arr}	$\sigma_{\Delta\theta}$	$\sigma_{\hat{\theta}}$	$\sigma_{\delta\theta}$
I	4 m	30 ps	5,000	1	0.16″	5.2″	22 μas
II	10 m	10 ps	10,000	1	0.33″	1.8″	1.5 μas
III	10 m	3 ps	20,000	10	0.66″	0.52″	0.056 μas

$t_{obs} = 10^4$ s for a pair of Sun- like stars at 100pc

Exoplanet Detection





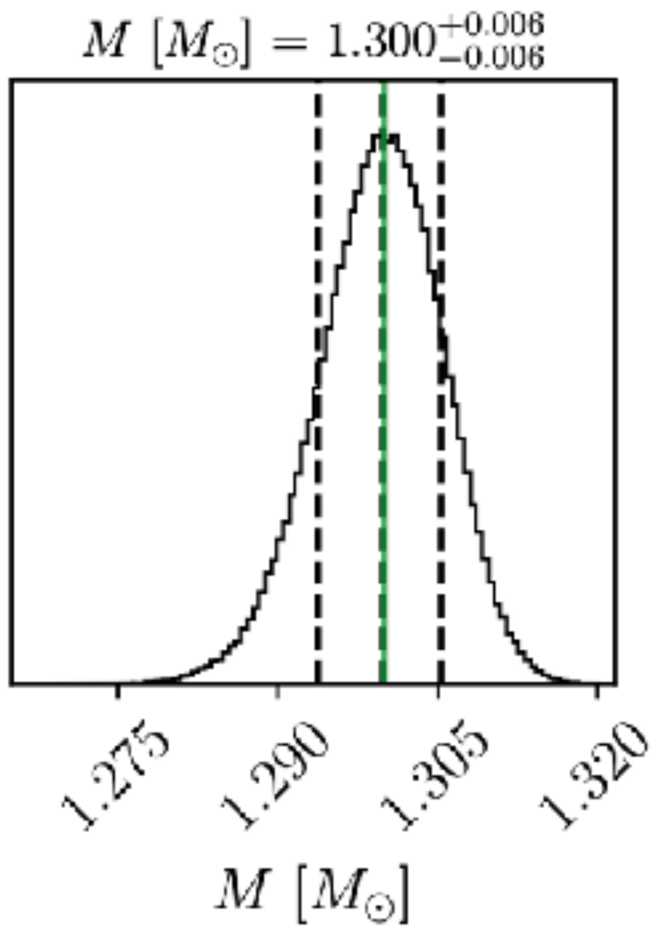
- Look for stellar wobble induced by exoplanet

$$\Delta\theta_{\rm star} \sim \frac{M_{\rm p}}{M_{\rm star}} \frac{a_{\rm p}}{D} \approx 0.15\,\mu{\rm as}$$

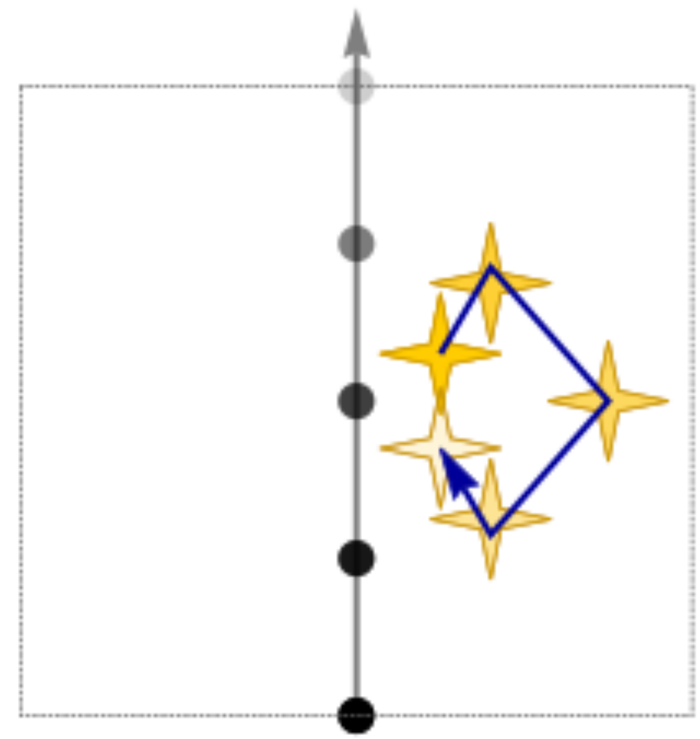
- EPIC could detect Earth-like planets around Sun-like stars where other techniques are limited
- Most stars in binaries: automatically good targets for intensity interferometry

[Van Tilburg, **MB**, Galanis, Weiner, 2307.03221]

Applications: Stellar Microlensing



STELLAR MASS



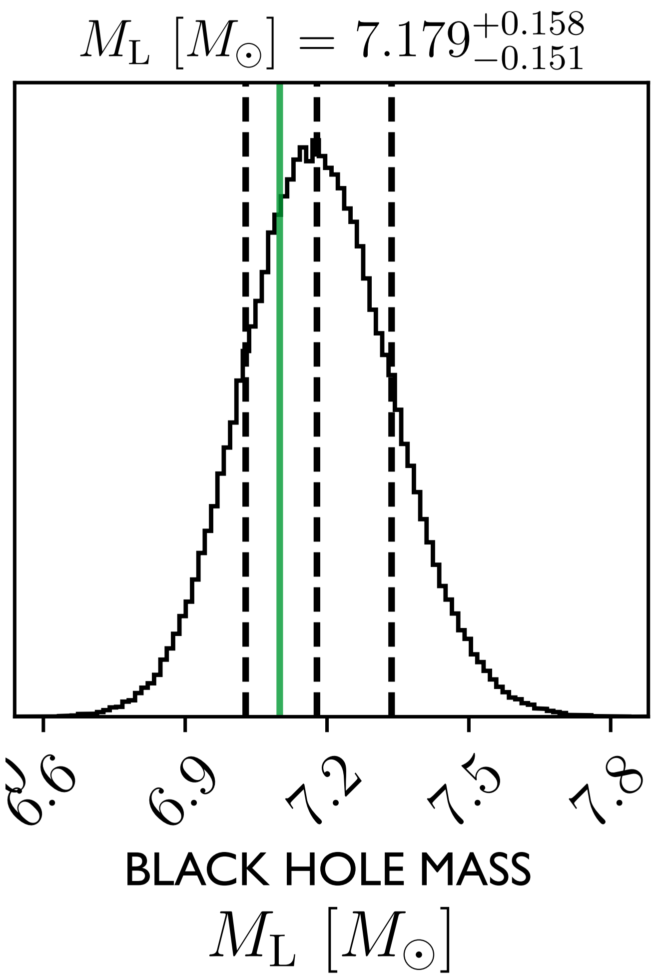
$$\theta_E = \sqrt{\frac{4GM_L}{D_L}\frac{D_{LS}}{D_S}} \sim 3\,\mathrm{mas}\sqrt{\frac{M_L}{M_\odot}\frac{\mathrm{kpc}}{D_L}}$$

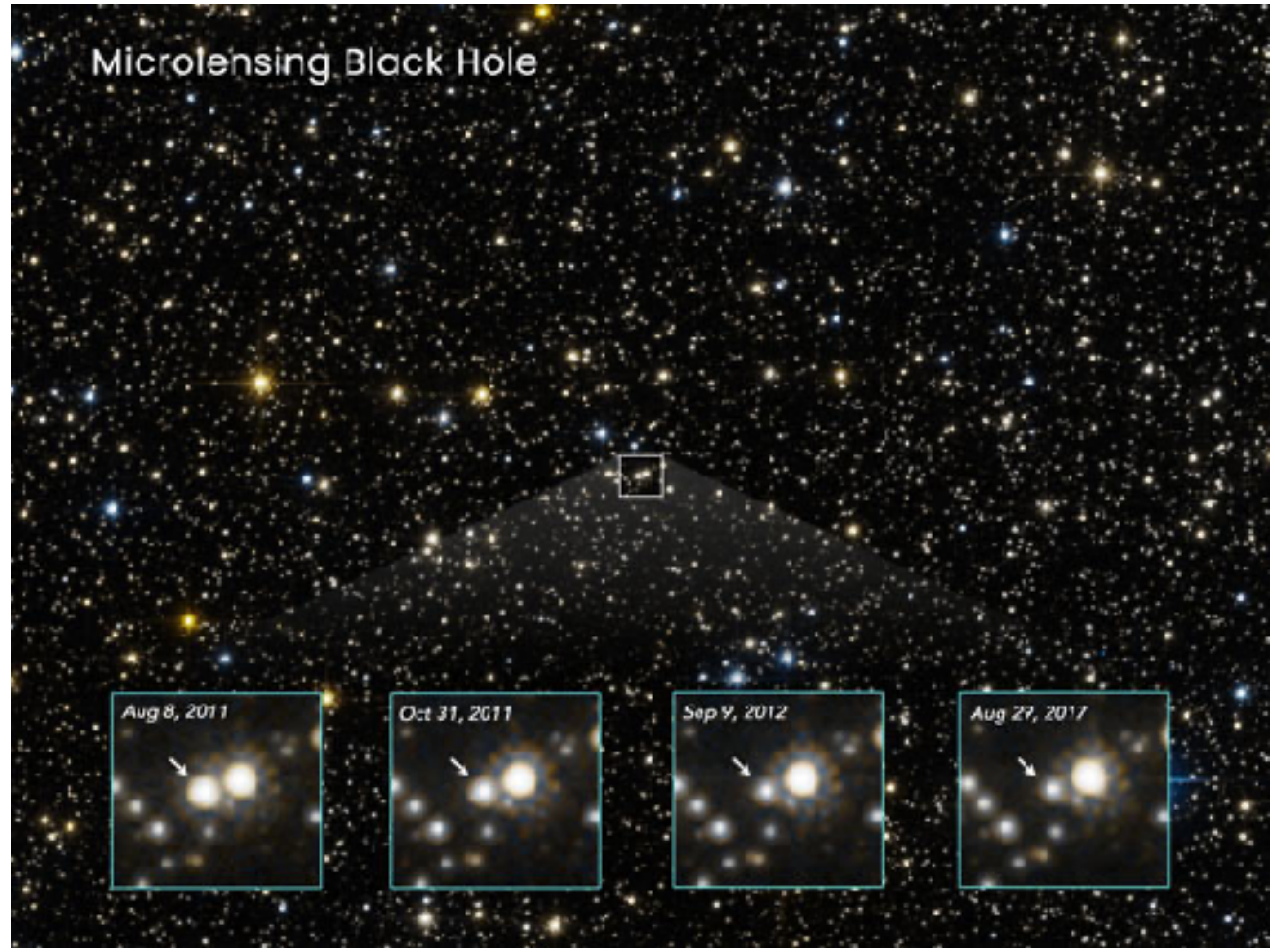
- Determine poorly known stellar separations 10μas within only two observing nights and two baselines.

- Assuming 6 relative separation measurements over a year around closest approach, determine mass to per mil precision: compare to 15% for Gaia end-of mission

[Galanis, Van Tilburg, **MB**, Weiner, 2307.06989]

Applications: Dark Microlensing



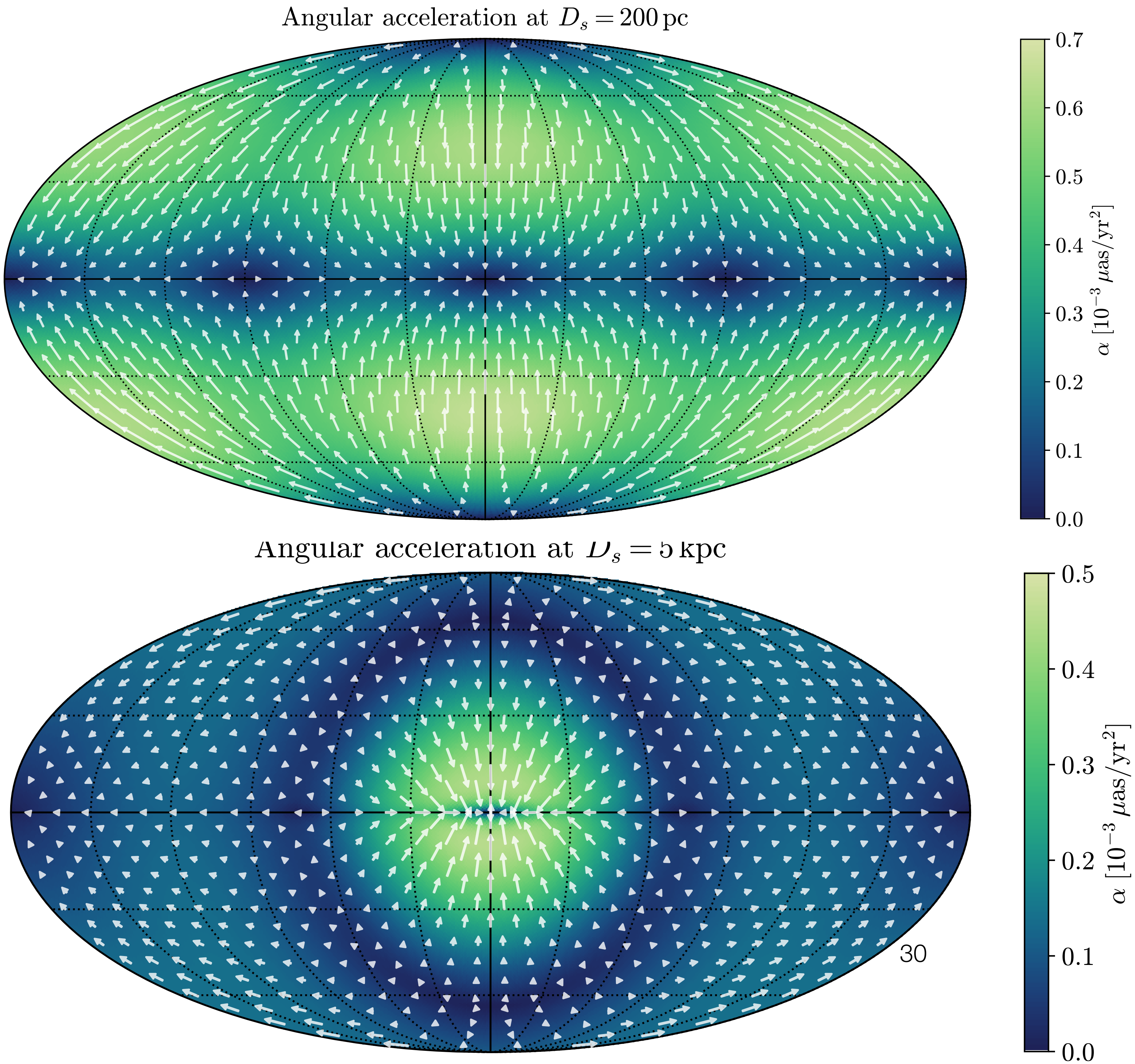


- Mock data set of six relative separation measurements over two years during the closes approach of the two images of MOA-2011-BLG-191/OGLE-2011-BLG-0462
- Determine black hole mass to 1.7% precision: compare to 18% using HST astrometry

[Galanis, Van Tilburg, **MB**, Weiner, 2307.06989]

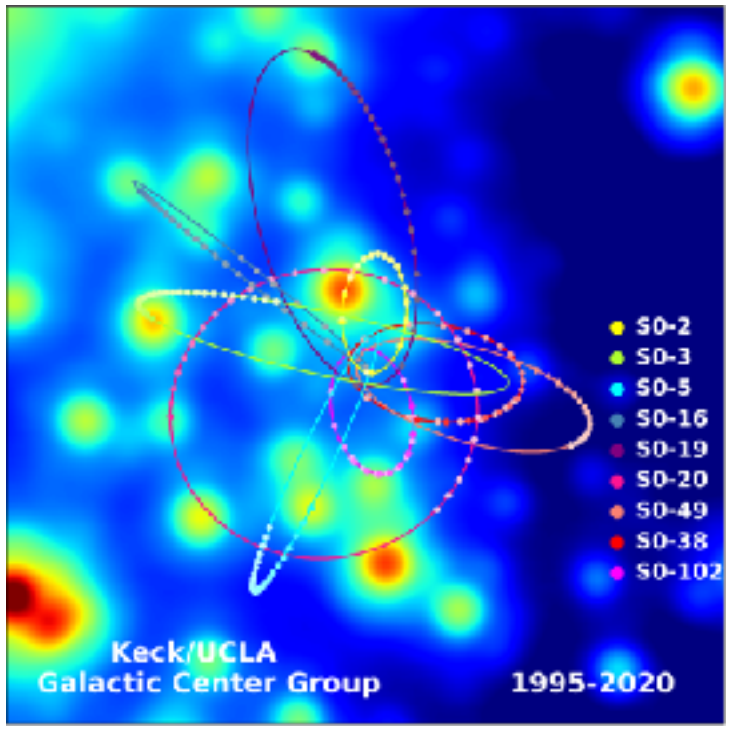
Applications: Galactic Accelerations

- Map relative transverse accelerations of accidentally close (in angle) stars
- EPIC Phase III could reach 0.2 nas/yr^2 for monthly observations over 30 yrs



[Galanis, Van Tilburg, **MB**, Weiner, 2307.06989]

Future measurements of our Black Hole?



Ghez UCLA Galactic Center Group, Keck Observatory Laser Team.

Jacob Crawford

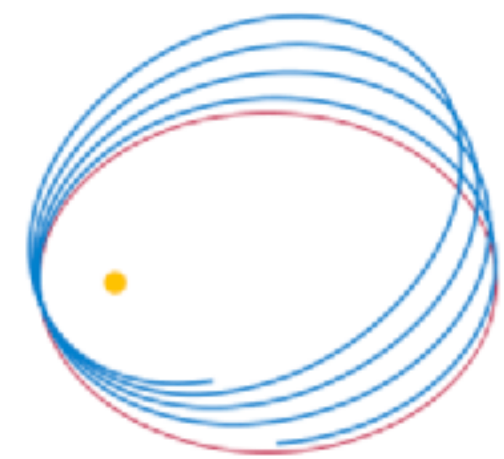
- ☑ Precession due to Schwarzschild: ~24 μas/yr

  GRAVITY Collaboration A&A 636, L5 (2020)

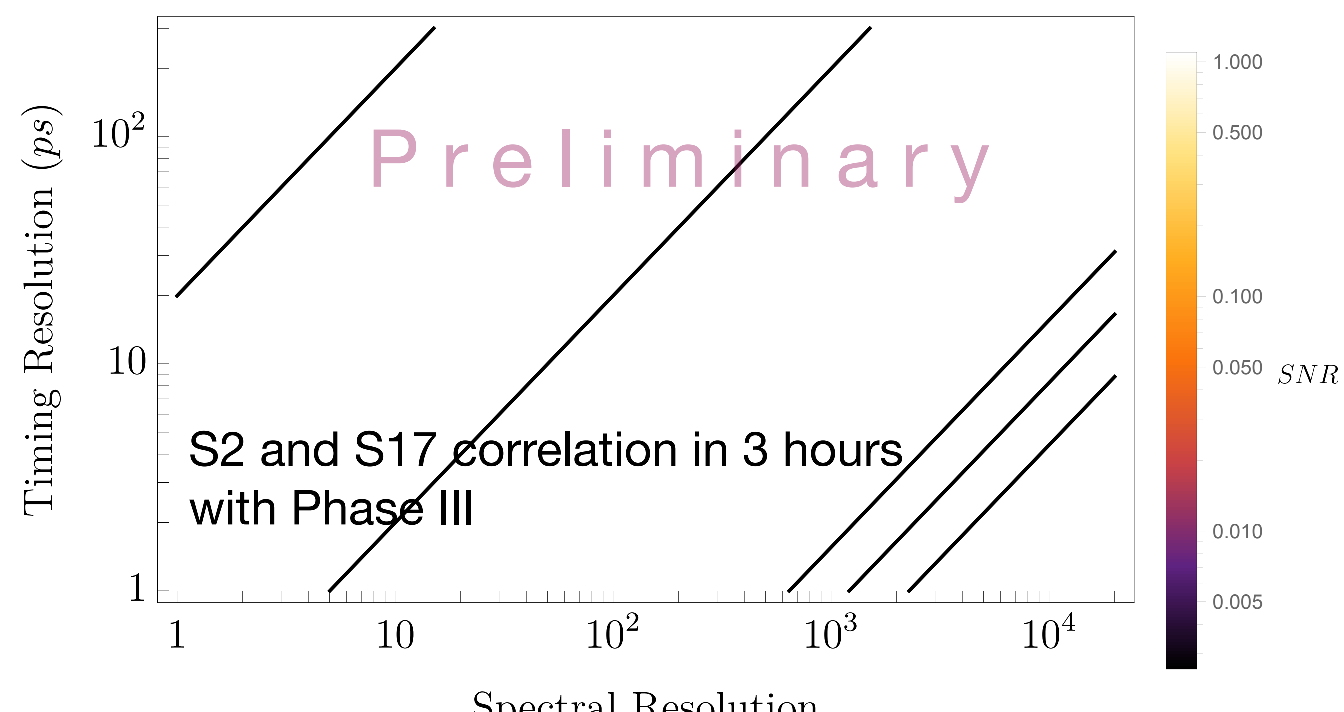
- Lense-Thirring Precession ~0.2 μas/yr

  EPIC Phase III 2035?

- Quadrupole Induced Precession ~0.002 μas/yr



Enhanced quadrupole e.g. due to superradiance may also be observable



[**MB**, J. Crawford, N. Dalal, M. Galanis, in prep]

EPIC: Laboratories in the Sky

Throughout the ages, the stars have taught us about the fundamental constituents of the universe and our place in it

- Intensity Interferometry provides unprecedented relative astrometry measurements for specific narrow angle targets

- Technological improvements in fast multiplexed single photon detectors will give parametrically higher SNR enabling a range of new science applications

- Extended Path Intensity Correlation (EPIC) concept increases field of view to greatly extend capabilities without losing