Coherence in the sky: precision astrometry with intensity interferometry

Masha Baryakhtar

International Workshop on New Opportunities for Particle Physics

July 19, 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

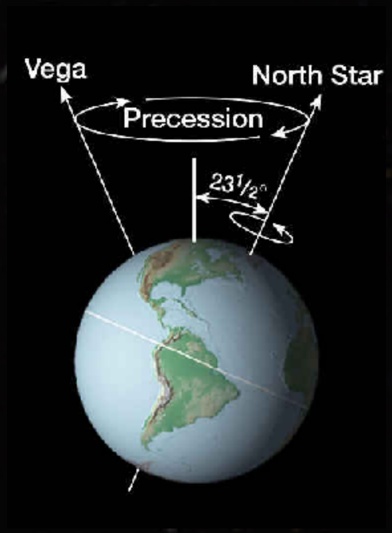
Laboratories in the Sky: New Physics from the Stars

Xing Jing Star manual (~350 BC)

Astronomer Shi Shen created a star catalogue containing 93 Constellations and the names of 810 stars, 121 of which are catalogued with their location leading to the first comprehensive star map.

Led to predictions of solar eclipses and comet arrivals

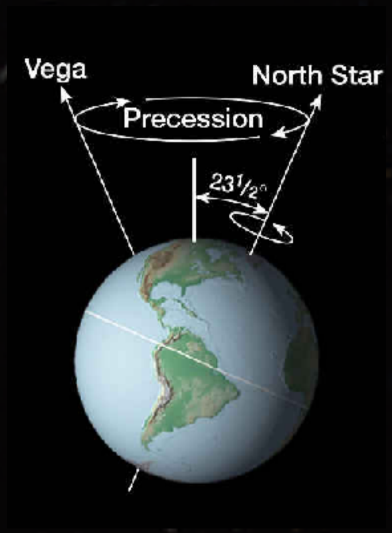
Laboratories in the Sky: New Physics from the Stars



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

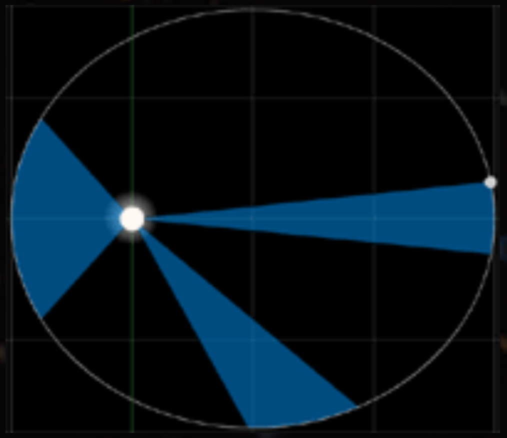
Discovered Earth's precession

Laboratories in the Sky: New Physics from the Stars



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

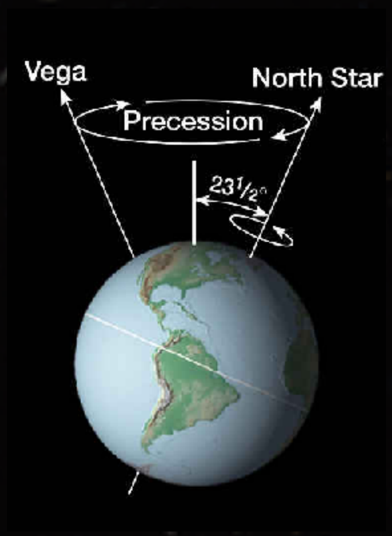
Discovered Earth's precession



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

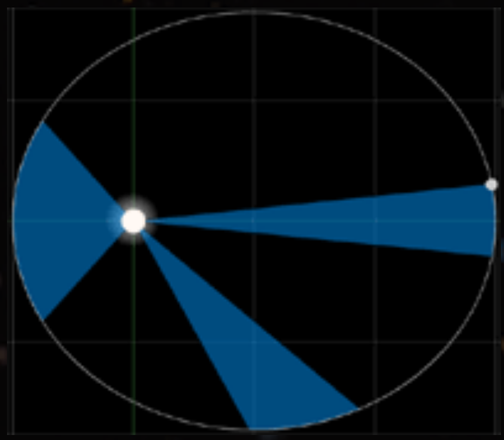
Kepler: Established laws of planetary motion

Laboratories in the Sky: New Physics from the Stars



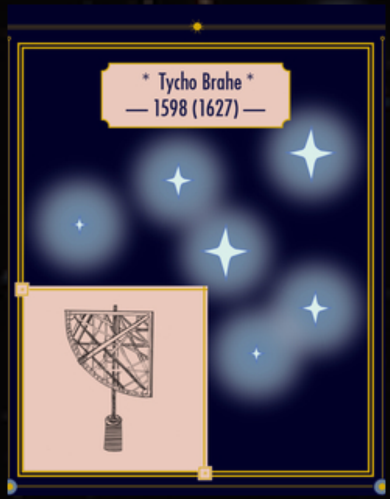
Hipparchus: cataloged hundreds of stars to 1° precision (angular size of the moon)

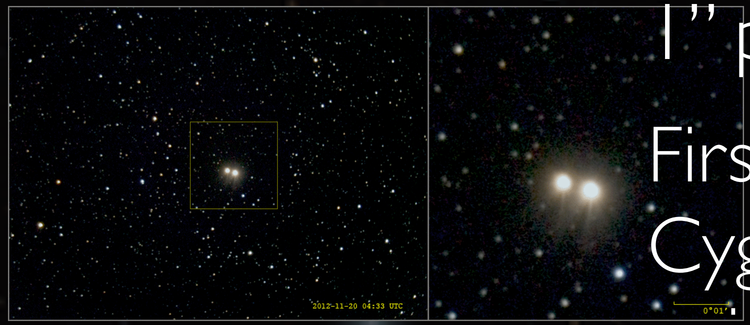
Discovered Earth's precession



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

Kepler: Established laws of planetary motion

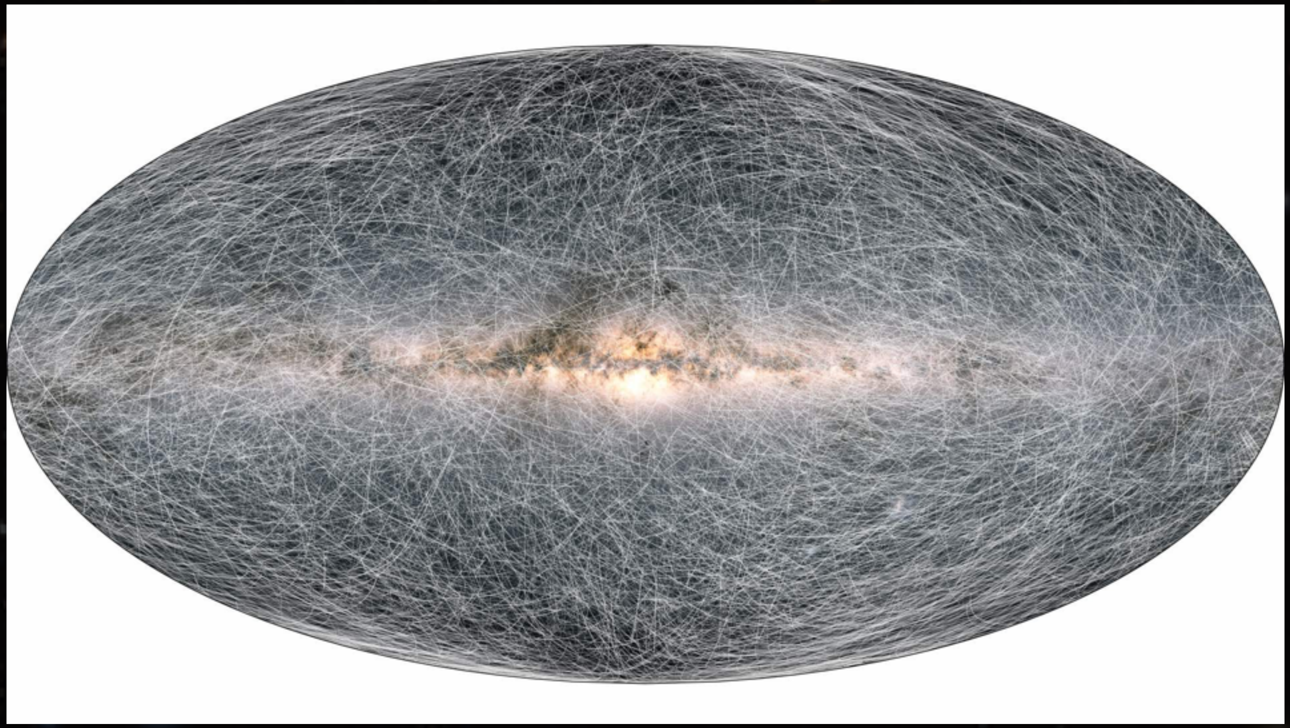




Friedrich Wilhelm Bessel: few stars measured to 1'' precision

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

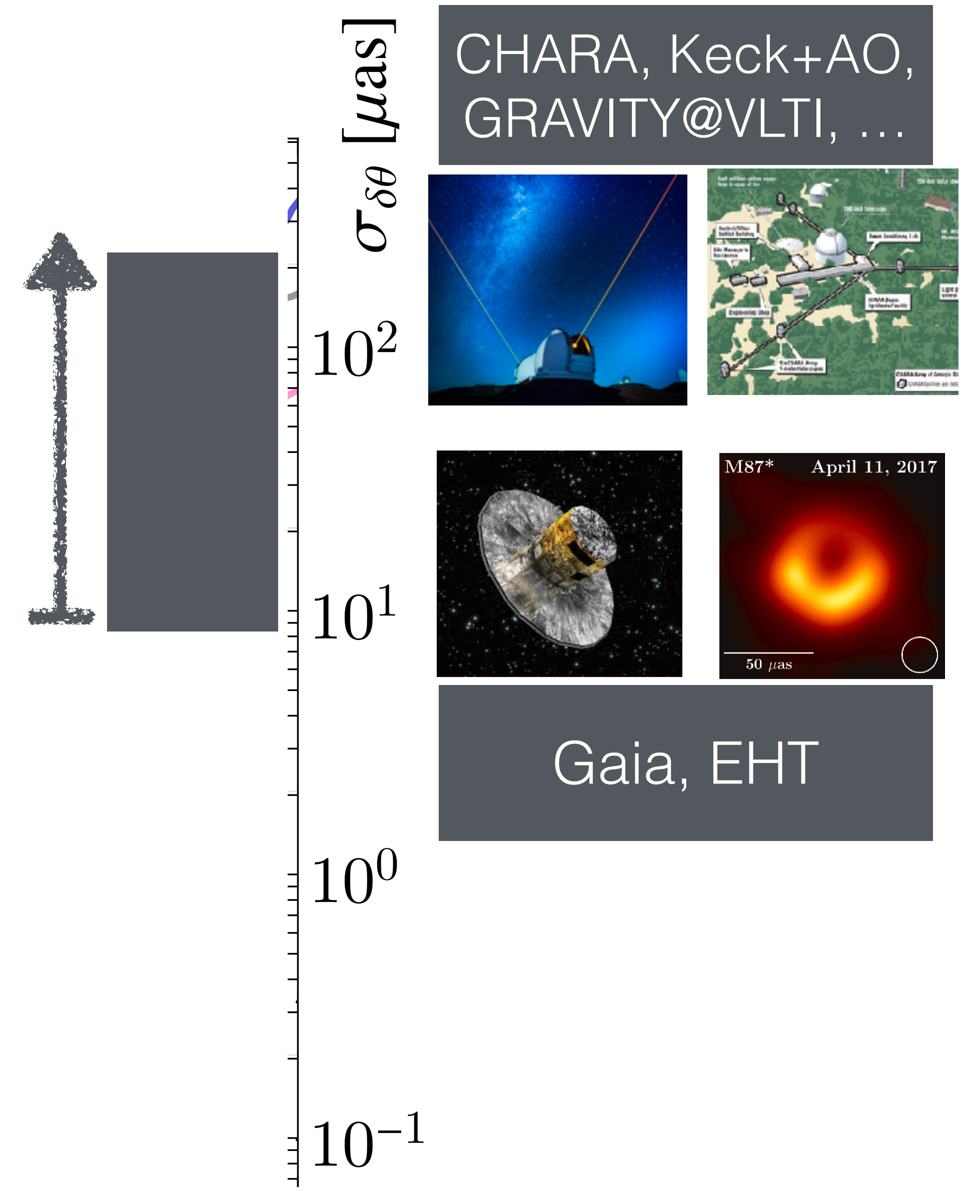
Discovery of supermassive black hole Sag A* and tests of GR

Today

Outline:

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

Intensity Interferometry Science Reach

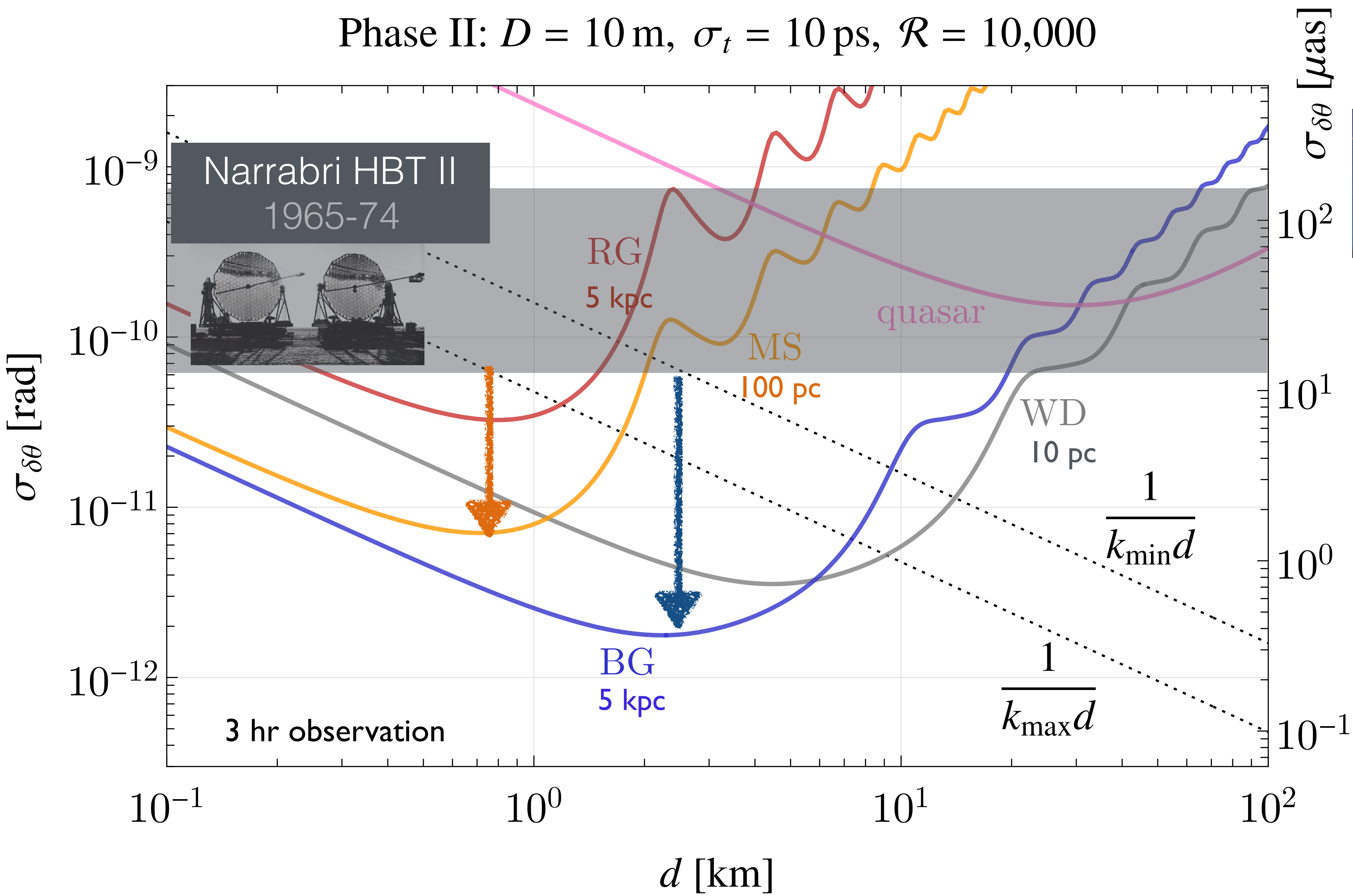


How do we push the precision beyond the current techniques?

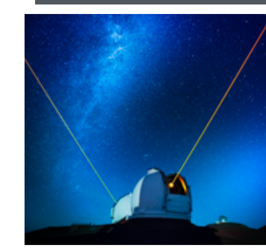
$$\sigma_{\theta_{\rm res}} \sim \frac{\lambda}{d} \approx 10^{-6}\,{\rm rad} \approx 0.4 \text{ arcsec} \qquad \sigma_{\delta\theta} \simeq \max\{\frac{\sigma_{\theta_{res}}}{\rm SNR}, \sigma_{\theta_{noise}}\}$$

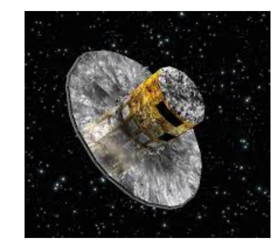
[Marios Galanis, Ken Van Tilburg, **MB**, Neal Weiner, 2307.03221]

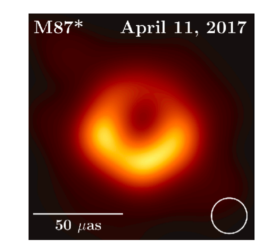
Intensity Interferometry Science Reach



CHARA, Keck+AO, GRAVITY@VLTI, …







Gaia, EHT

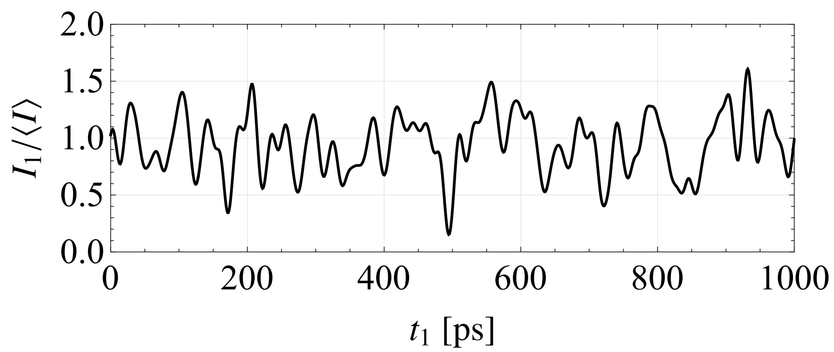
$$\sigma_{\theta_{\rm res}} \sim \frac{\lambda}{d} \sim \underbrace{10^{-12}\,\mathrm{rad}}_{0.2\,\mu\mathrm{as}} \left(\frac{\lambda}{500\,\mathrm{nm}}\right)\left(\frac{100\,\mathrm{km}}{d}\right)$$

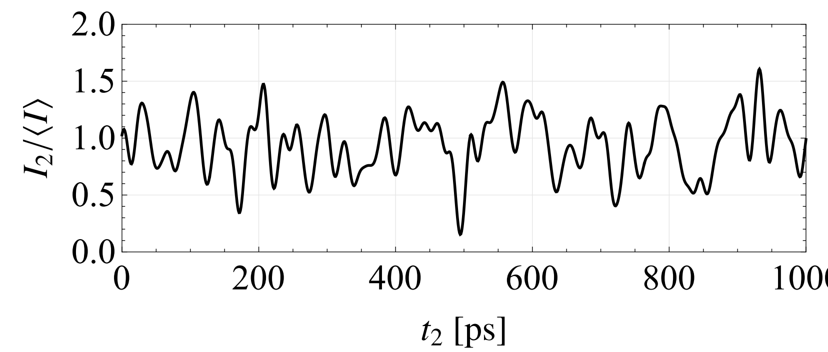
$$\sigma_{\delta\theta} \simeq \frac{1}{\mathrm{SNR}}\sigma_{\theta_{\rm res}}$$

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

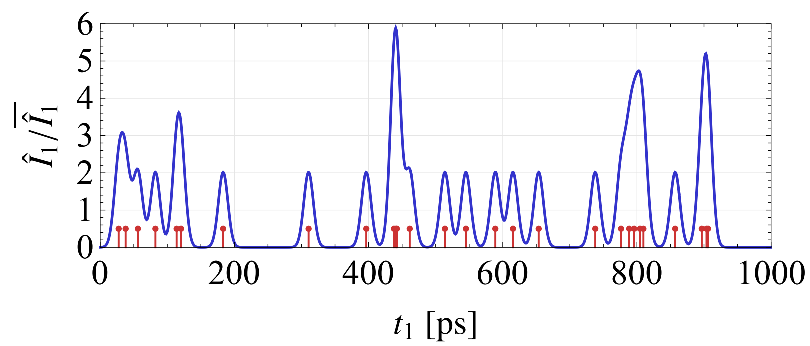
Intensity Interferometry

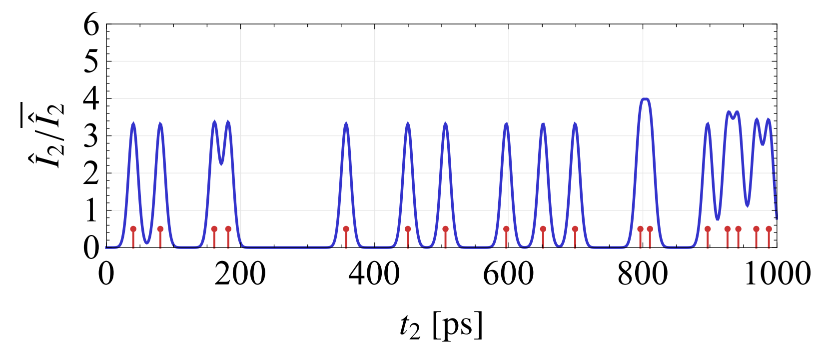
Random fluctuations in intensities

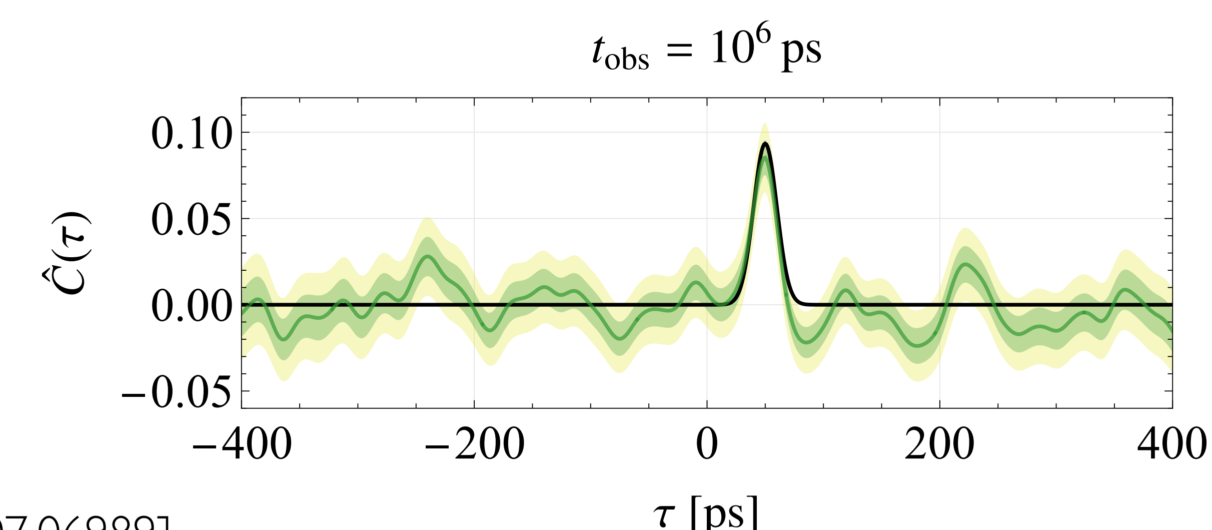




Result in correlations in photon counts

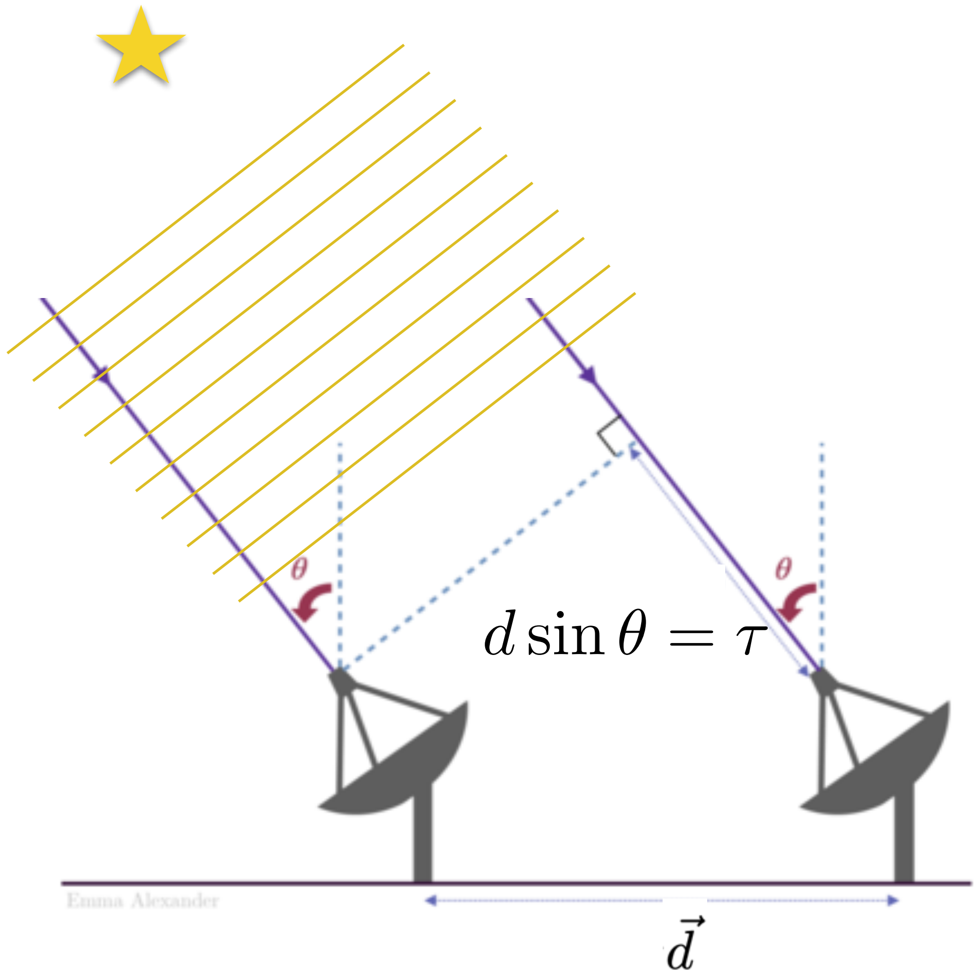






[Galanis, Van Tilburg, **MB**, Weiner, 2307.06989]

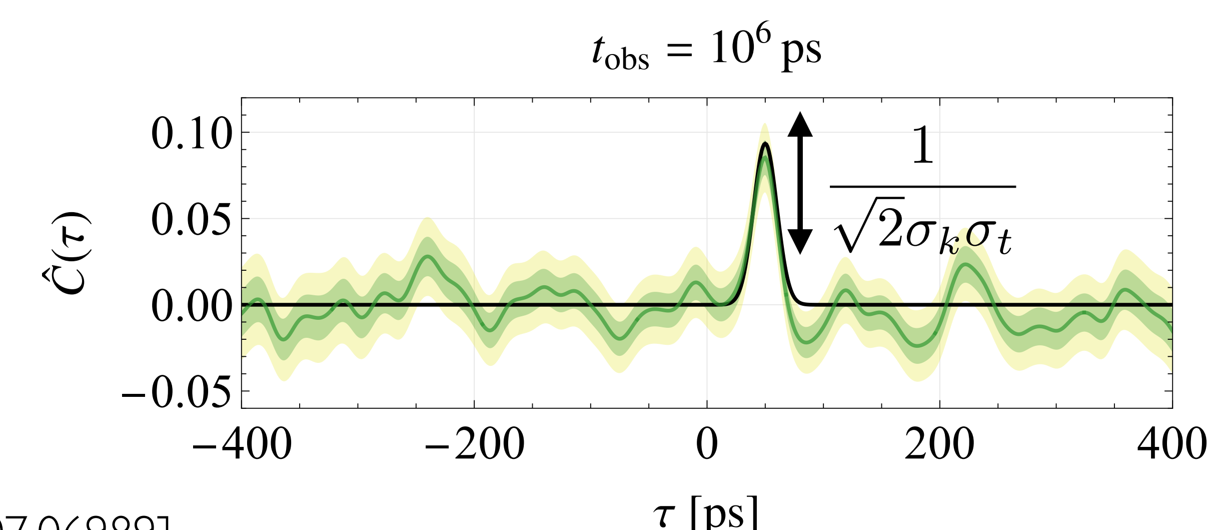
Intensity Interferometry



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

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

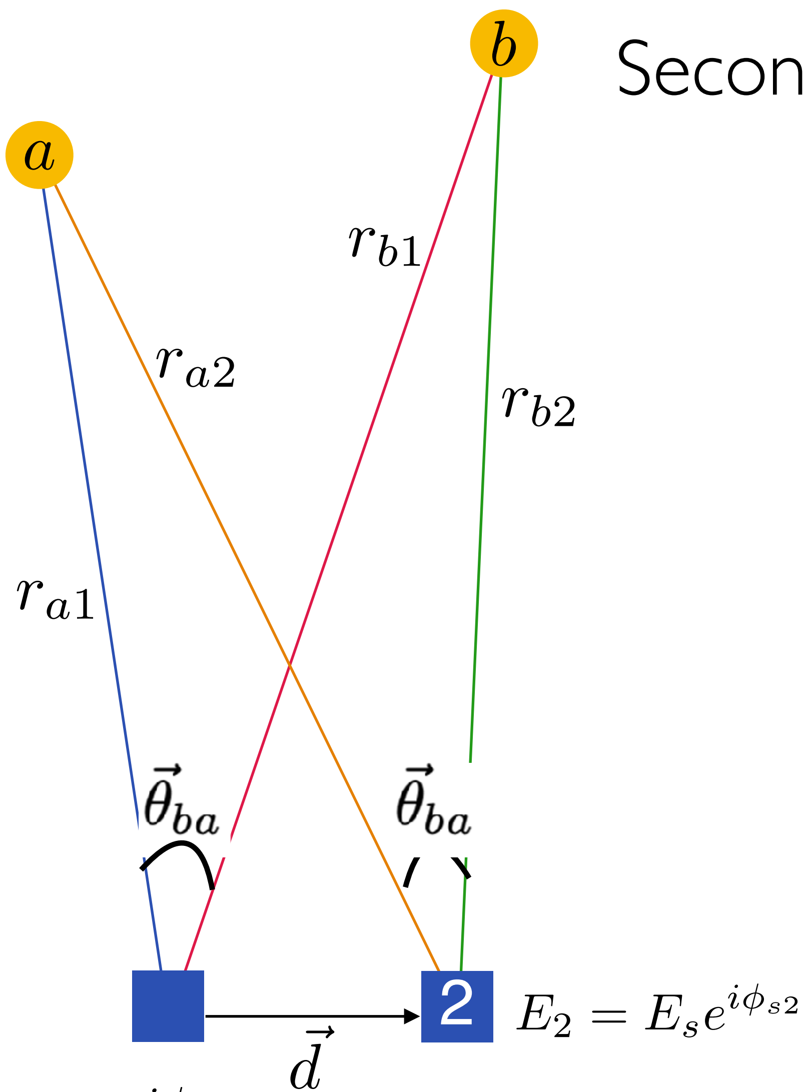
$$|\mathcal{V}|^2 \propto \left|\text{Fourier transform at angular wavenumber } k\vec{d}\right|^2$$



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

Intensity Interferometry

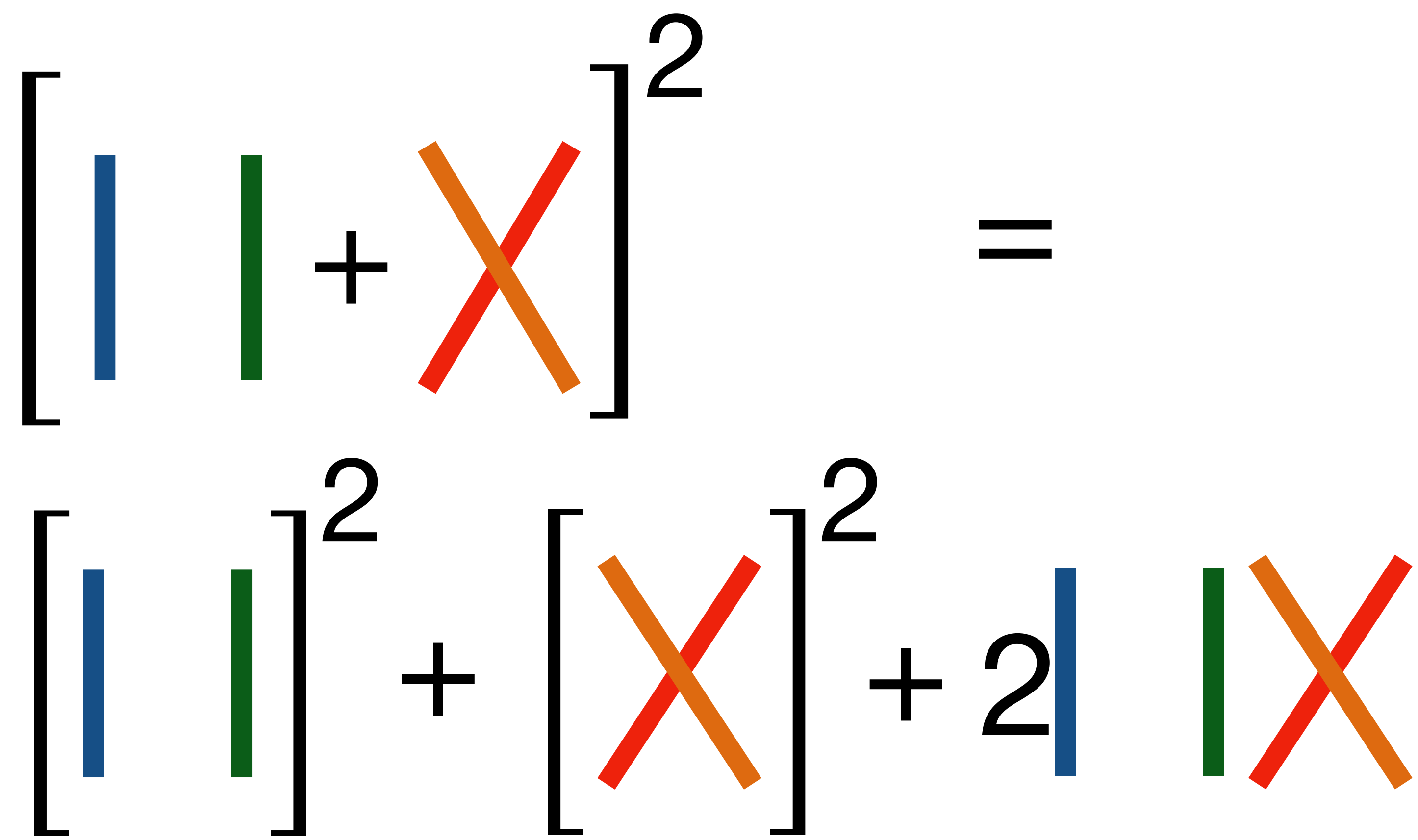
Second Order Correlations of Light



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

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

Classical wave interference *or* quantum mechanical constructive interference between indistinguishable two photon states:



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

"The Brown-Twiss effect, far from requiring a revision of quantum mechanics, is an instructive illustration of its elementary principles."
-- Nature 178 (1956)

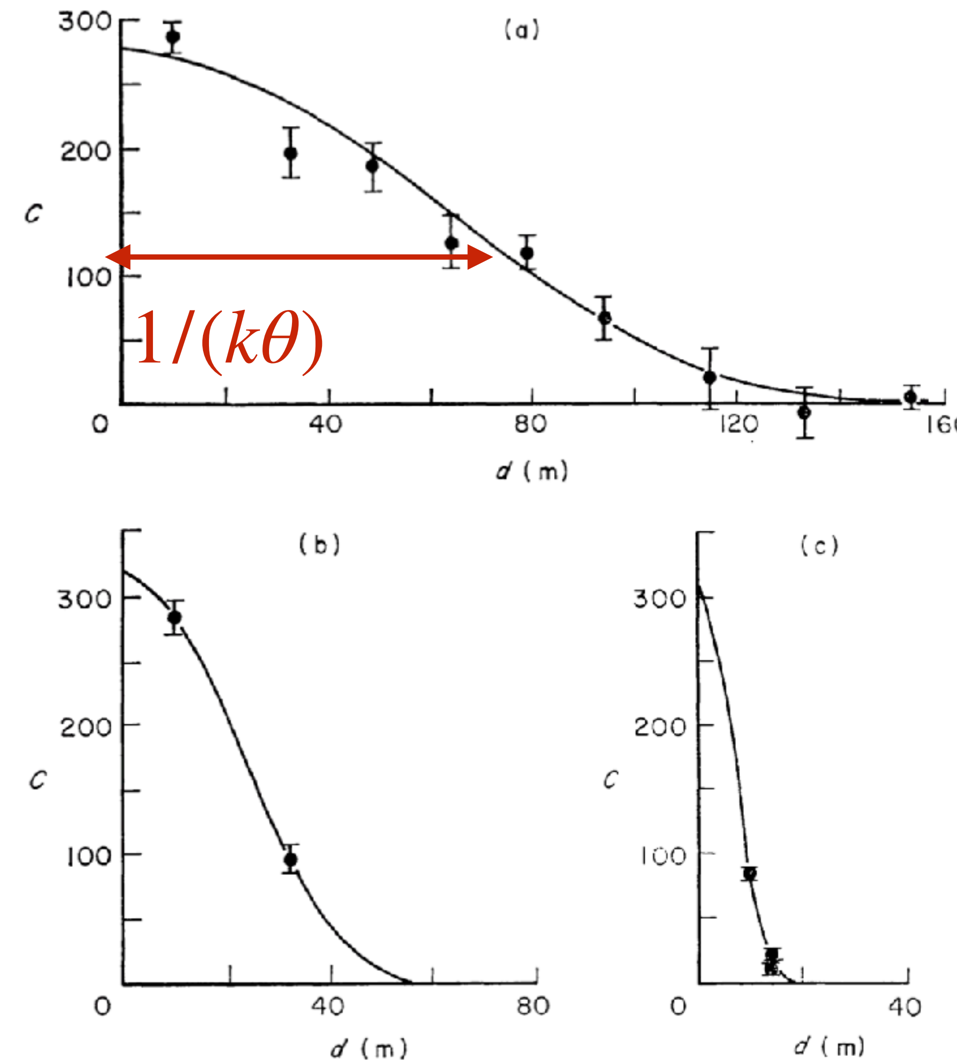
Edward Purcell

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

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

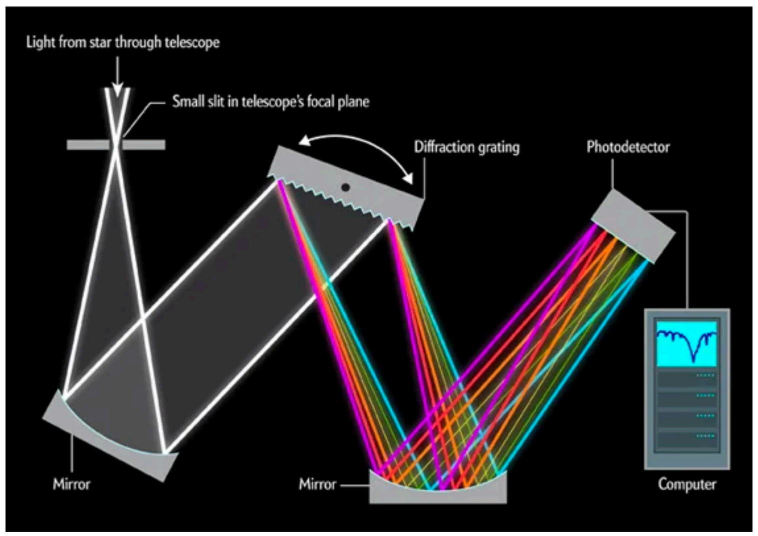


HBT made some of the most precise measurements of stellar diameters, comparable to modern optical interferometers, EHT resolution, end of mission Gaia centroiding precision

Overcoming Limitations: Signal to Noise Ratio

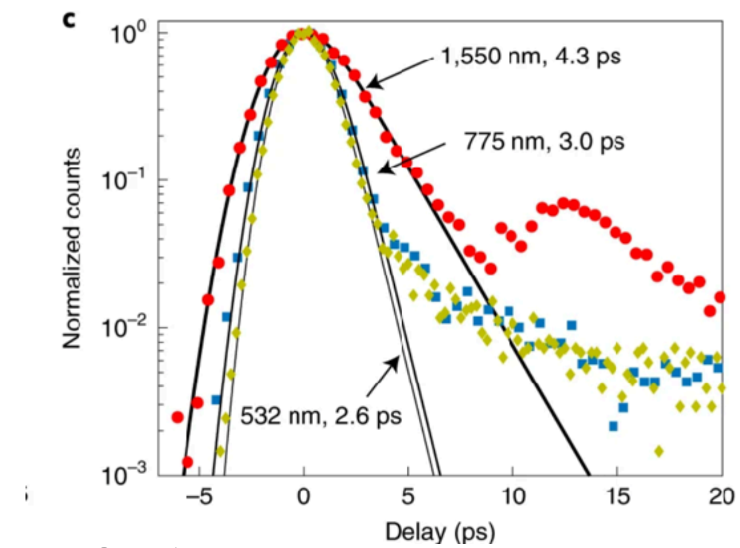
Why now: technological advances allow for fainter sources:

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)

Large Collecting Areas

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

Benchmark parameters for science cases:

Phase	D	σ_t	$\mathcal{R}$	$n_{\rm arr}$	$\sigma_{\delta\theta}$
I	4 m	30 ps	5,000	1	22 μas
II	10 m	10 ps	10,000	1	1.5 μas
III	10 m	3 ps	20,000	10	0.056 μas

For 3 hrs of observation for a pair of Sun-like stars at 100pc

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

Outline:

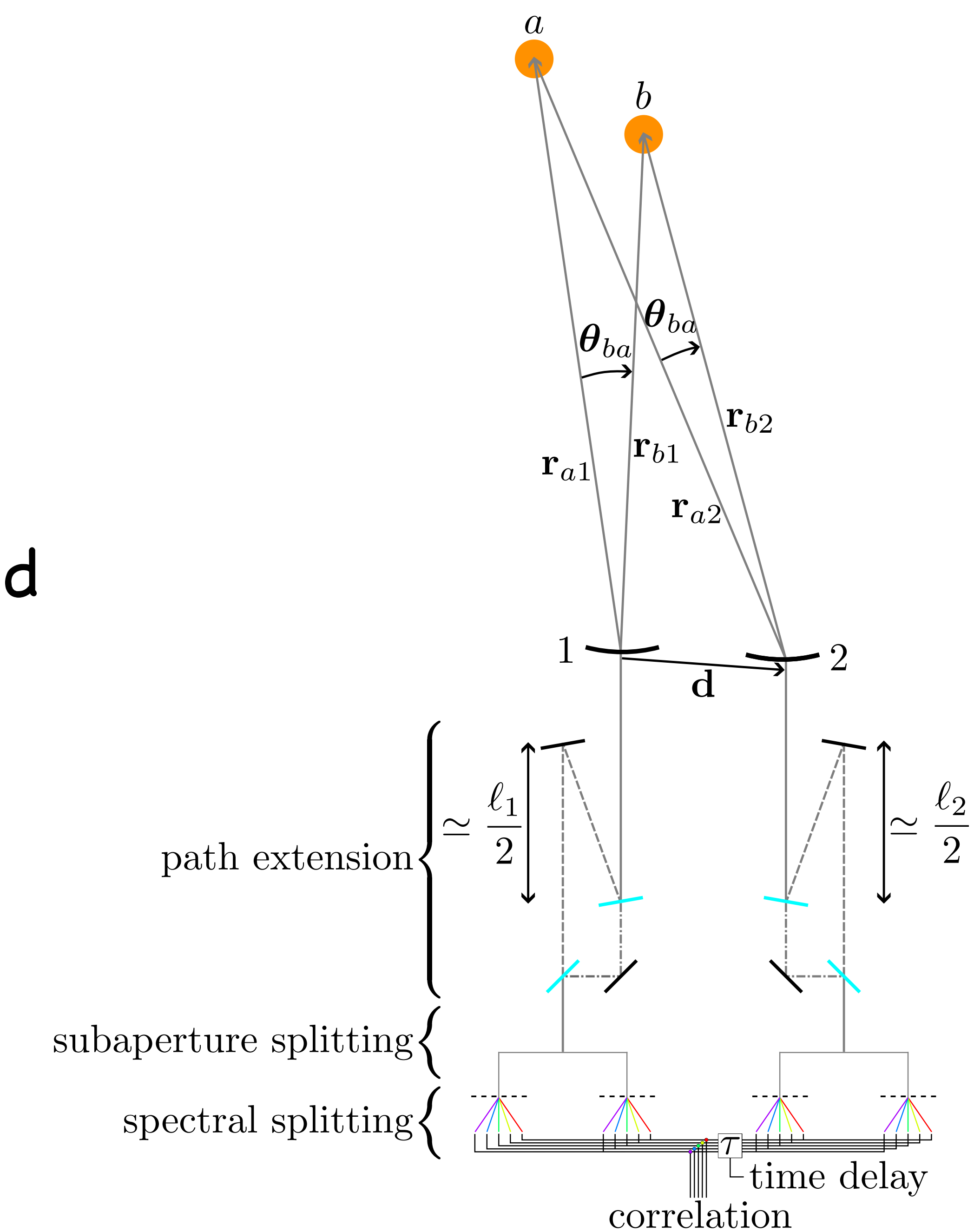
- Coherence in the sky: interfering intensities
- EPIC: extended path intensity correlation
- Measurements with precision relative astrometry

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]

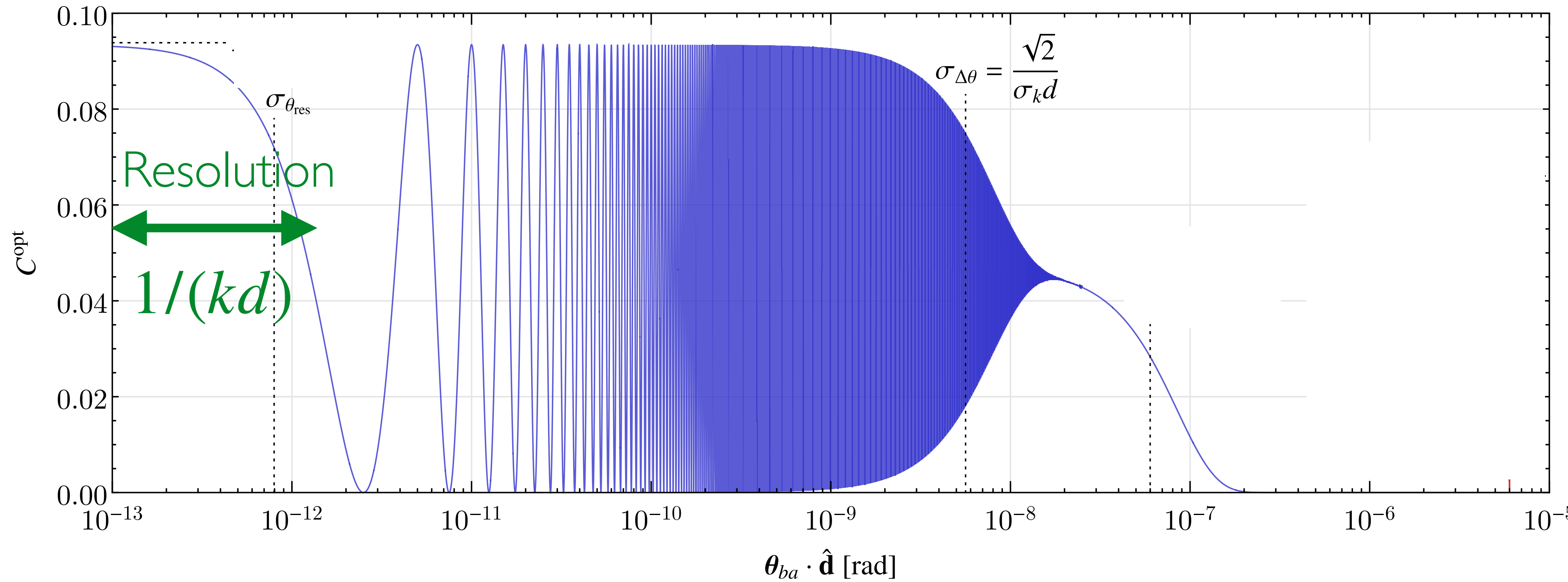
[Galanis, Van Tilburg, **MB**, Weiner, 2307.06989]

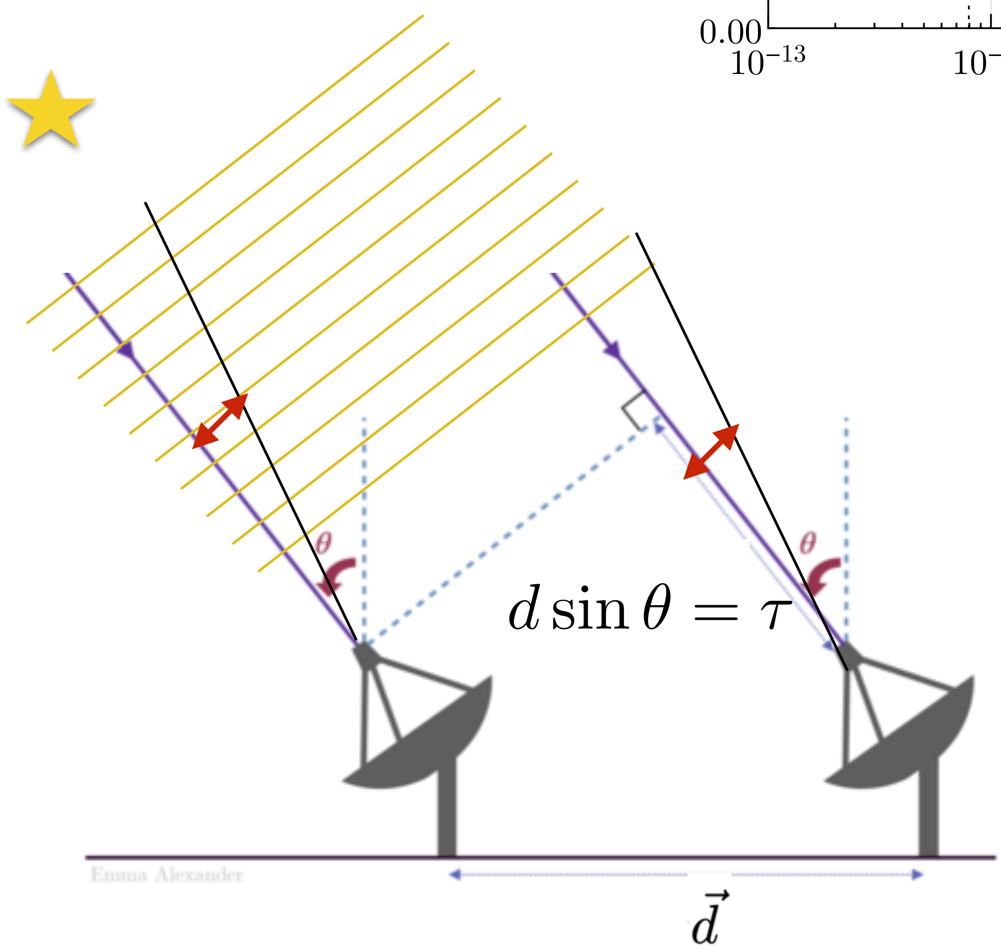
Ken Van Tilburg

Marios Galanis

Neal Weiner

Overcoming Limitations: Tiny Field of View

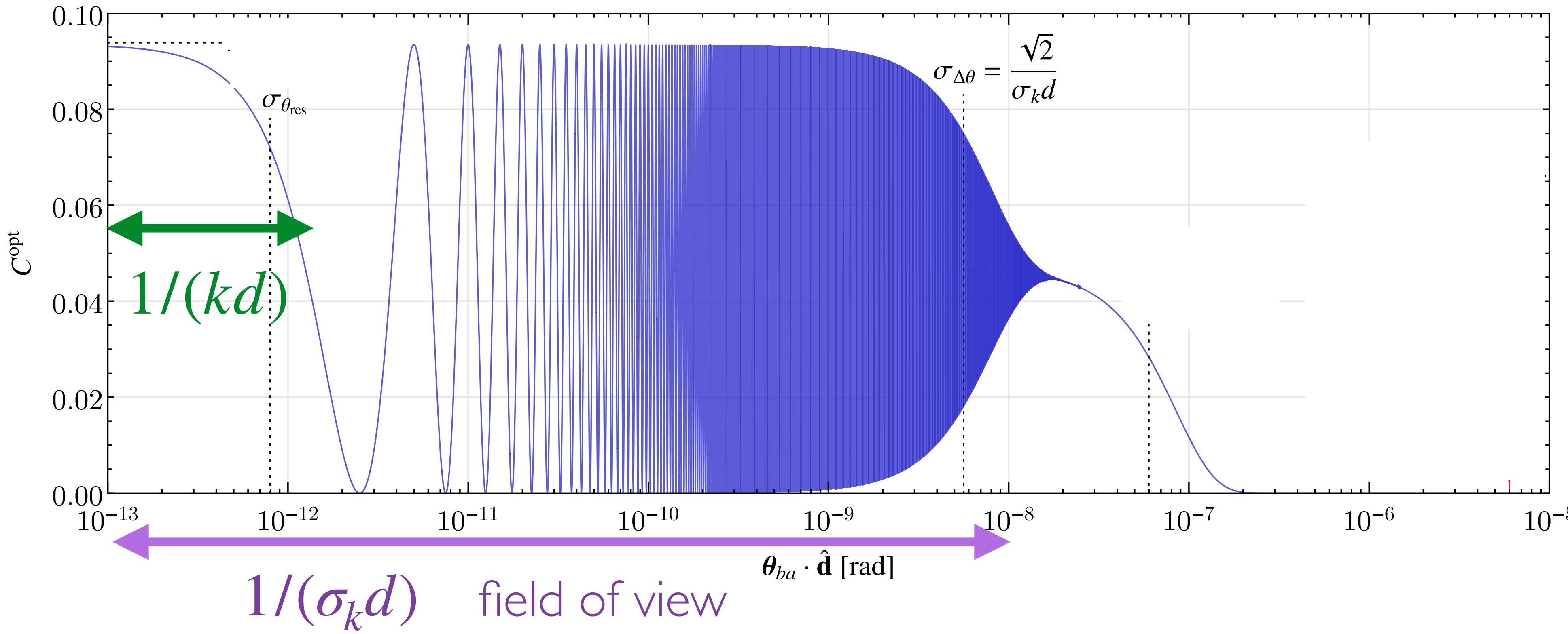


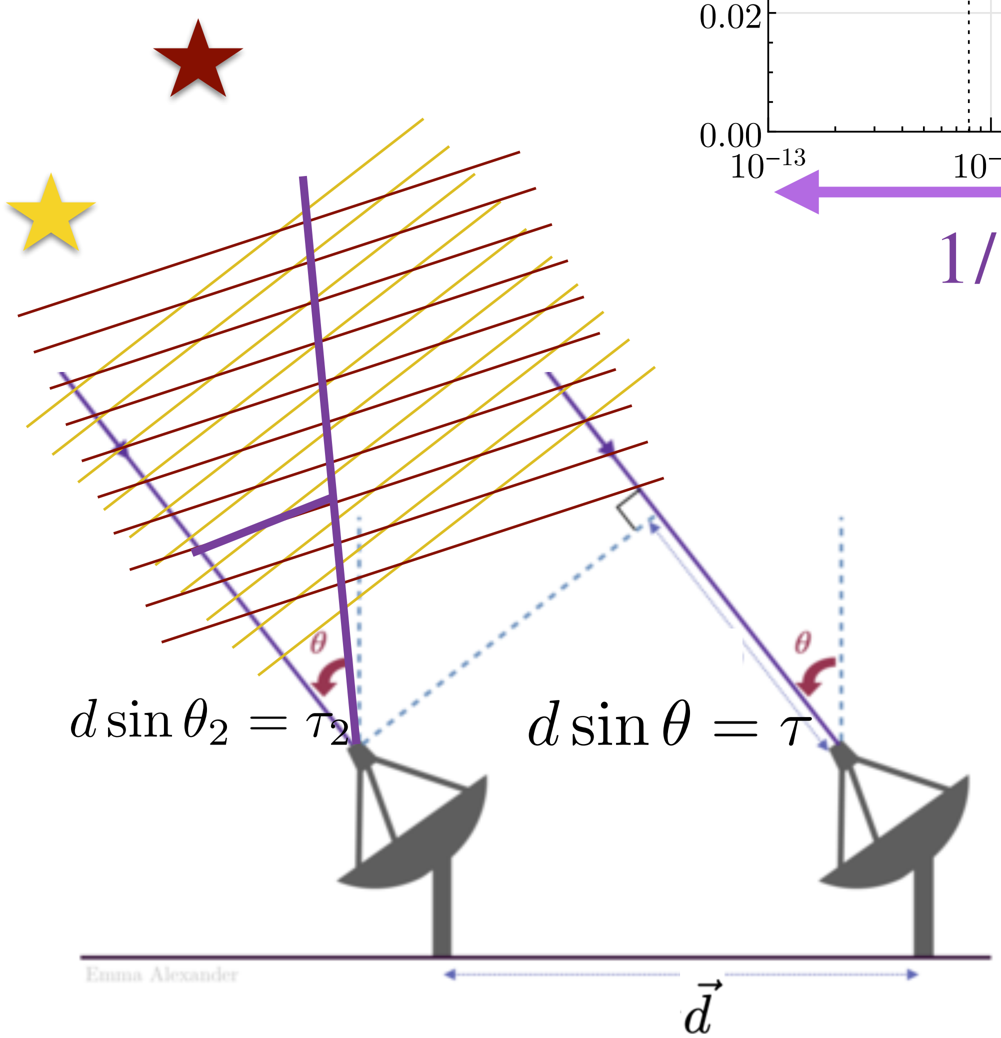


$$C = \frac{\langle I_1(t) I_2(t+\tau)\rangle}{\langle I_1\rangle \langle I_2\rangle} - 1$$

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

Overcoming Limitations: Tiny Field of View



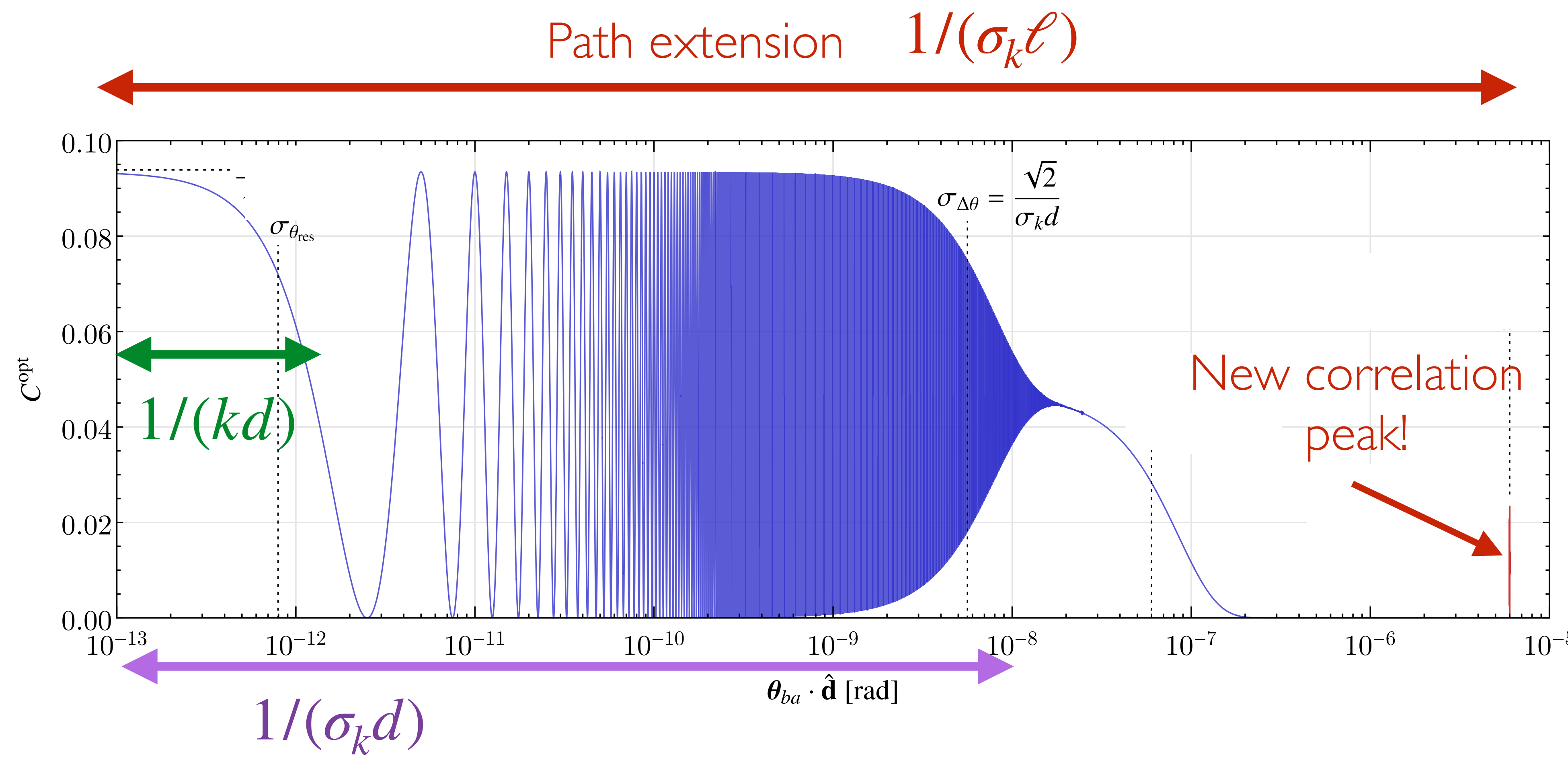


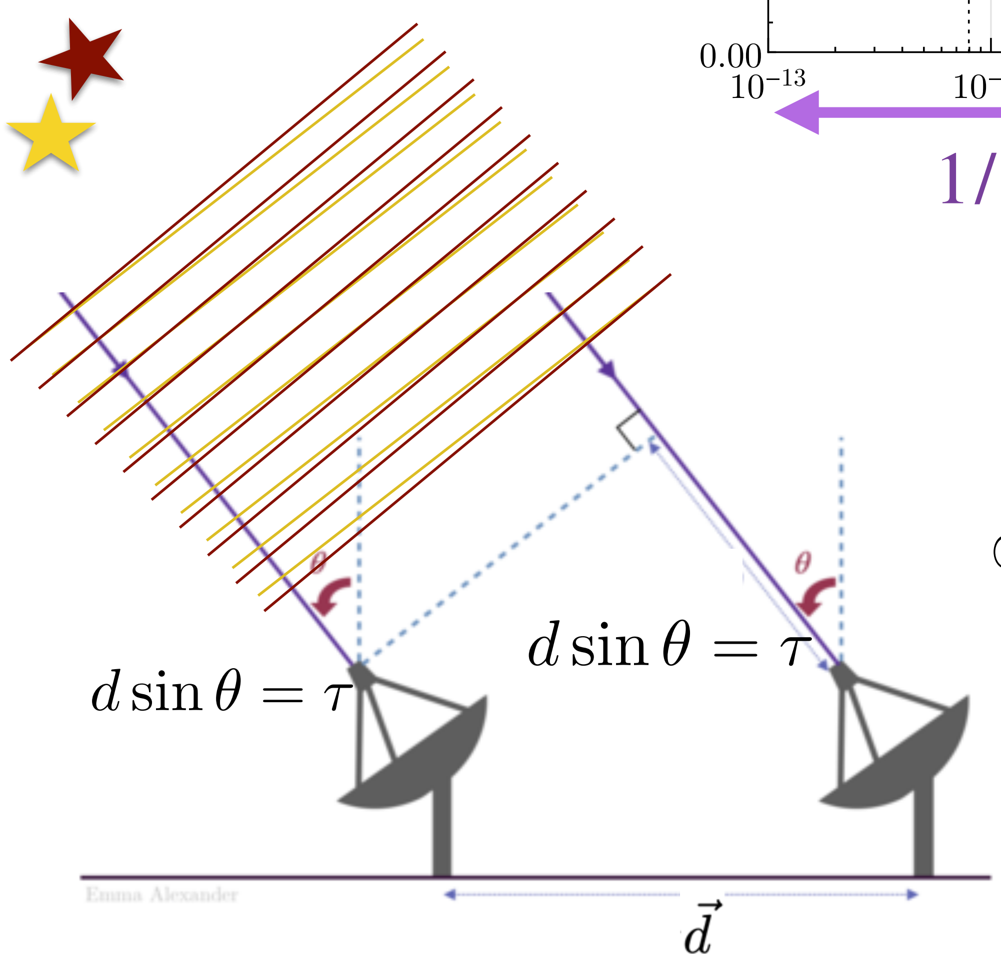
$$C = \frac{\langle I_1(t) I_2(t+\tau)\rangle}{\langle I_1\rangle \langle I_2\rangle} - 1$$

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

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



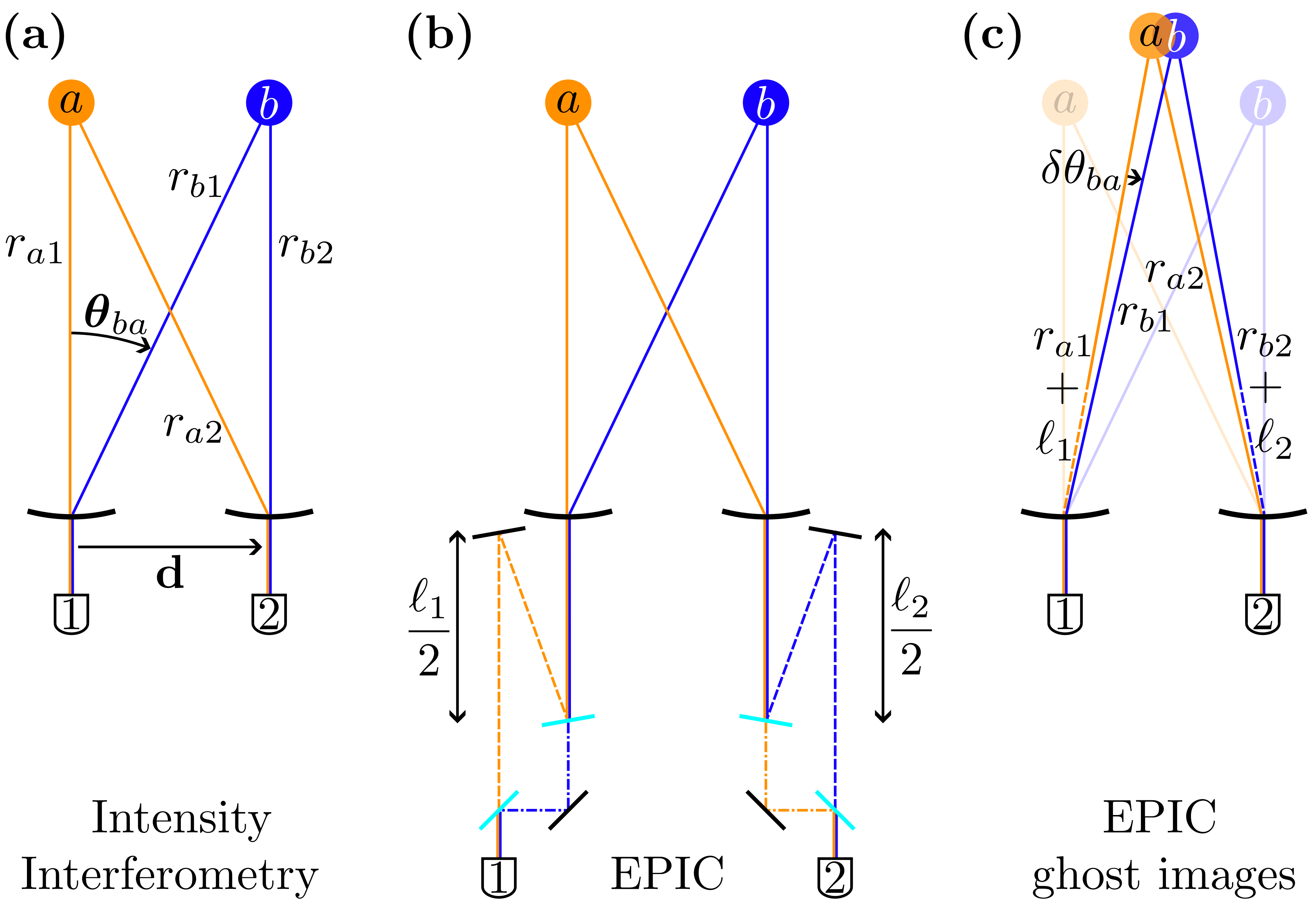


$$C = \frac{\langle I_1(t) I_2(t+\tau)\rangle}{\langle I_1\rangle \langle I_2\rangle} - 1$$

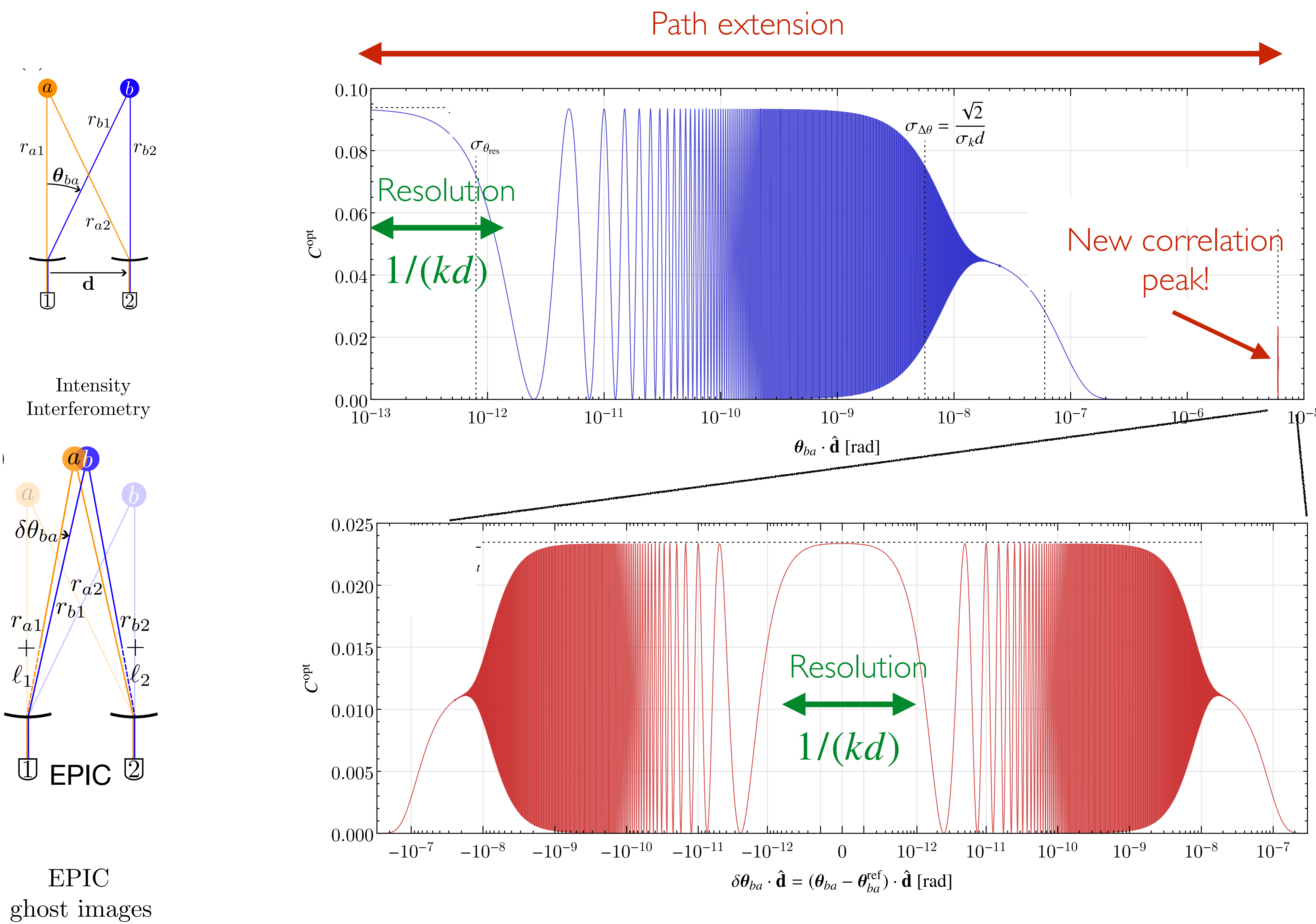
$$\propto \cos[k(\mathbf{d}\cdot\boldsymbol{\theta}_{ab} - 2\ell)] \exp\left\{-\frac{[\sigma_k(\mathbf{d}\cdot\boldsymbol{\theta}_{ab} - 2\ell)]^2}{4}\right\}$$

Simply add an optical path extension!

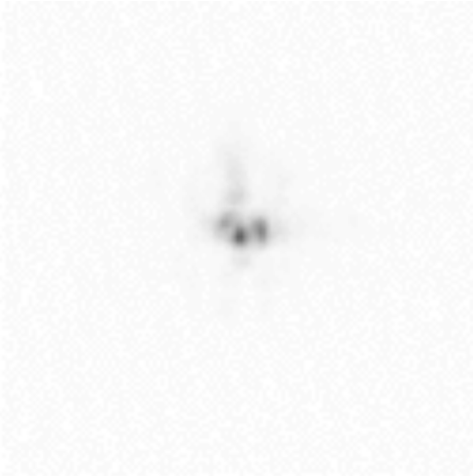
Overcoming Limitations: Extended Path

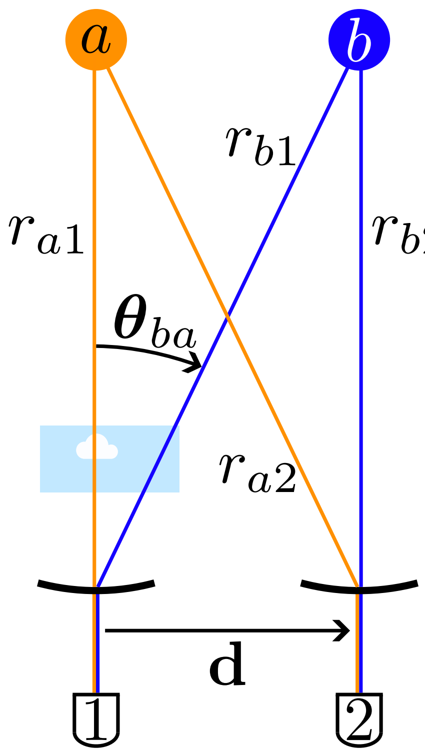


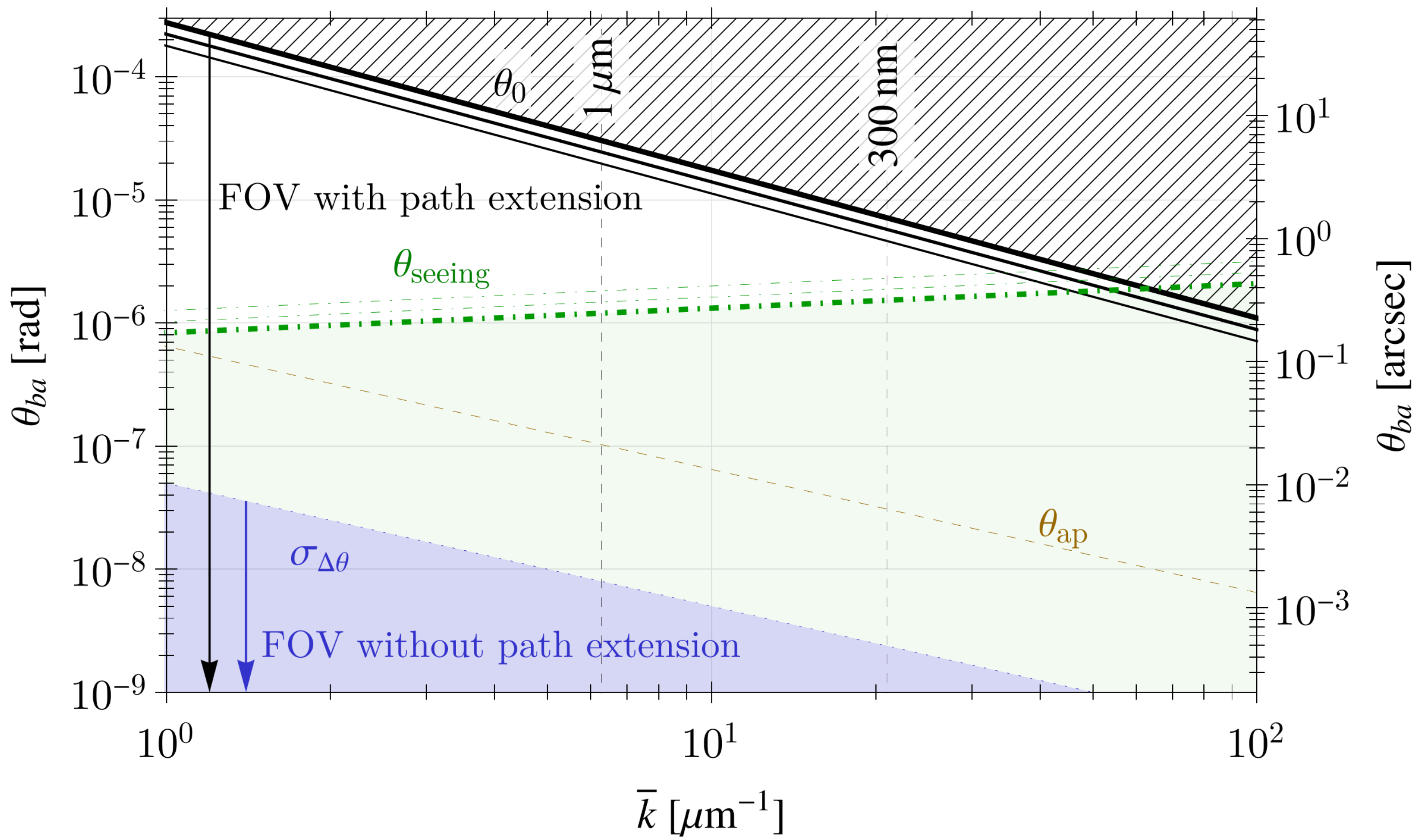
Overcoming Limitations: Extended Path



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.**"*

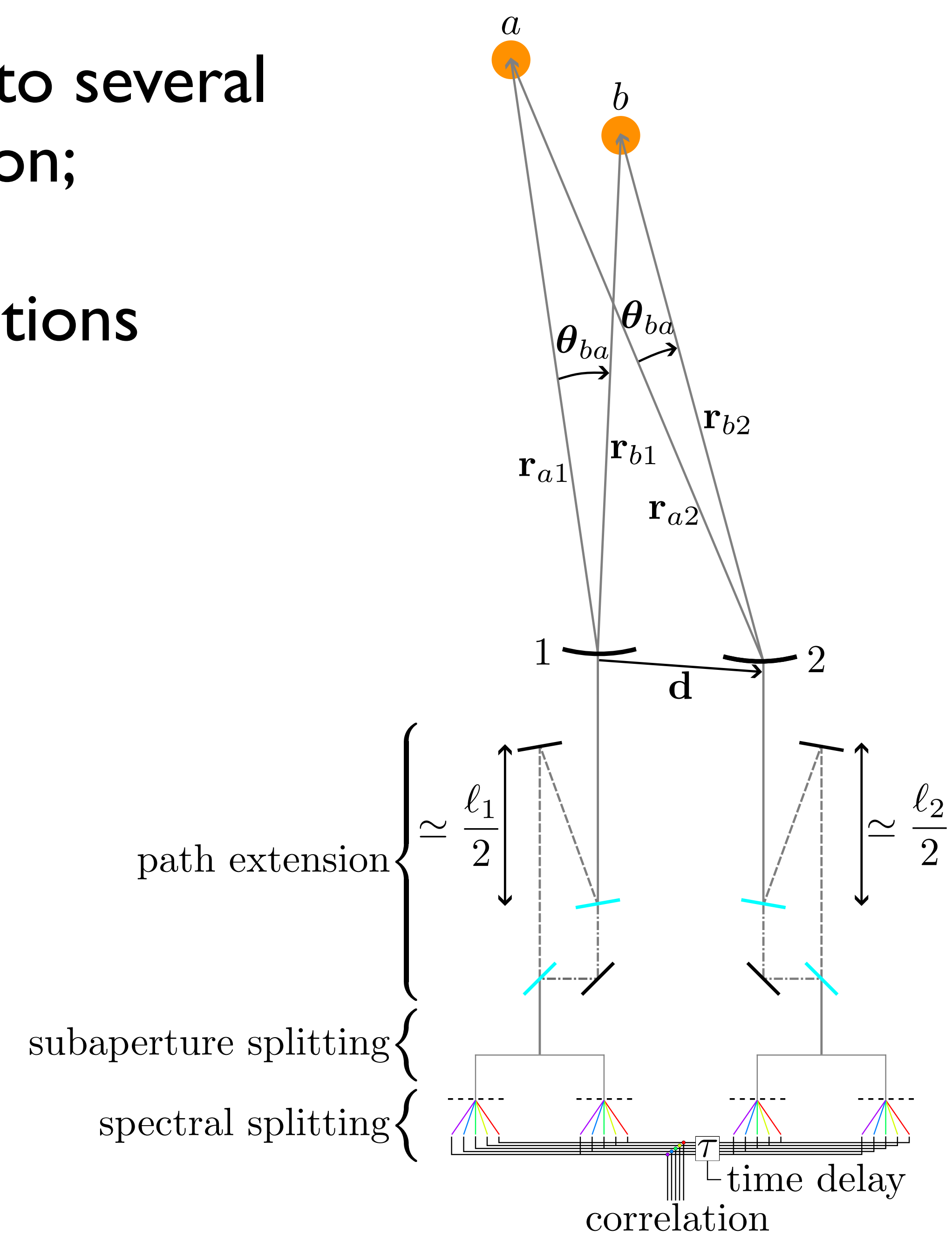
— Hanbury Brown, 1974

Intensity Interferometry Science Reach

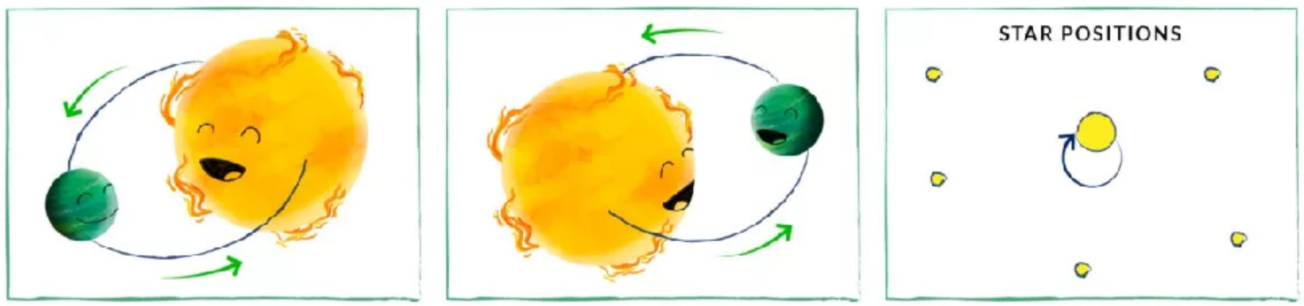
Measure motion of bright, closely separated (up to several arcsec) sources to unprecedented precision;

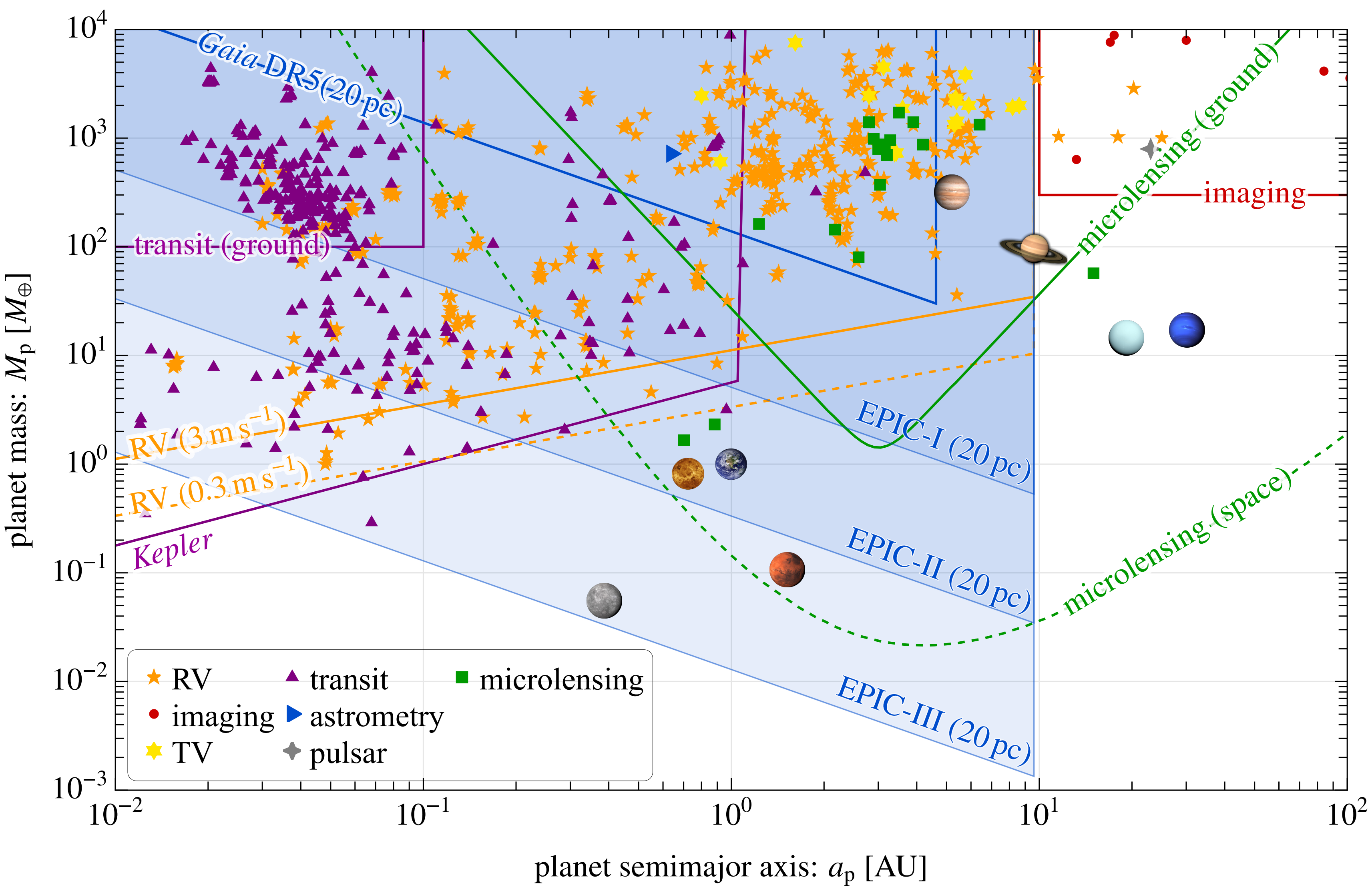
Robust to atmospheric and telescope distortions

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



Exoplanet Detection





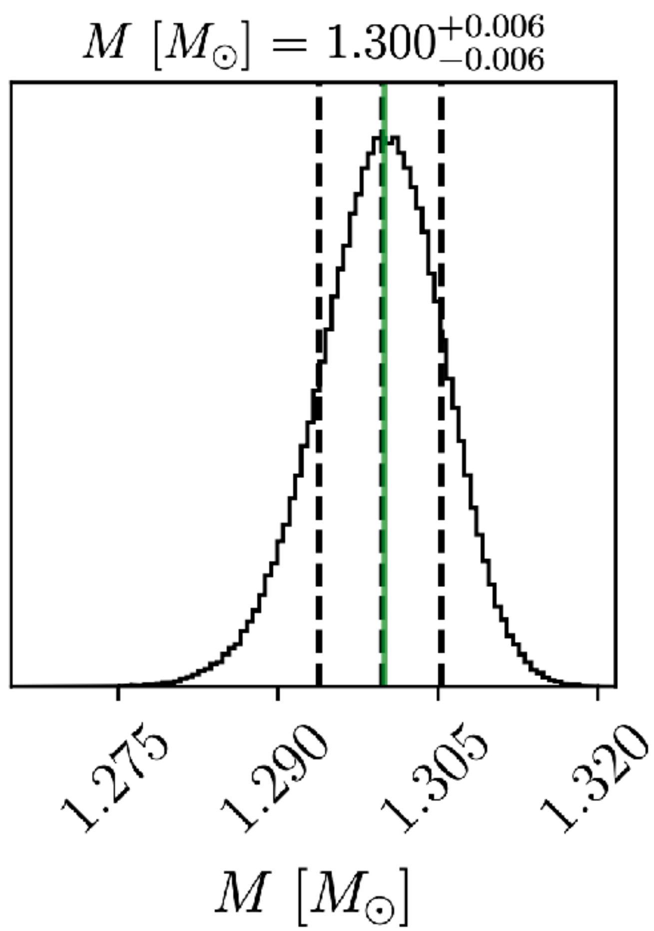
- Look for stellar wobble induced by exoplanet

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

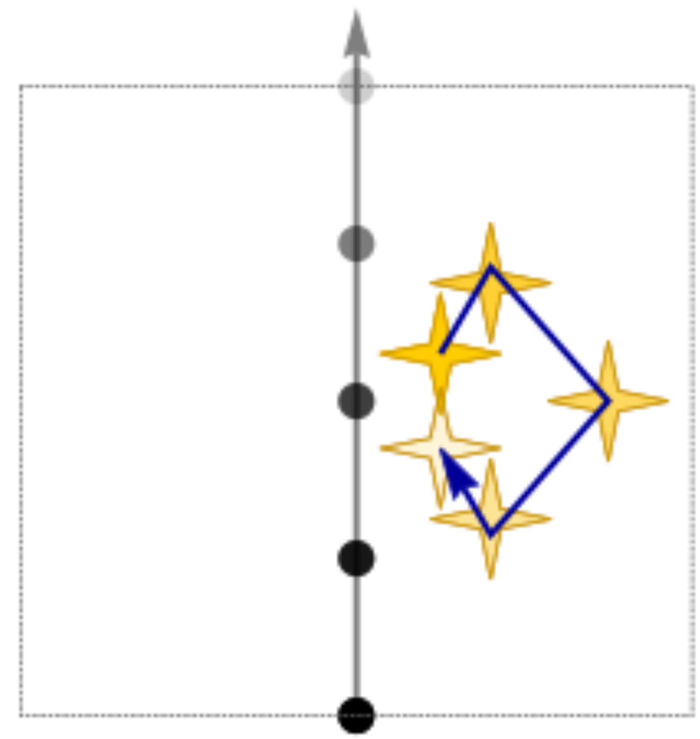
- EPIC could detect Earth-like planets around Sun-like stars where other techniques are limited
- Most stars in binaries: automatically good targets for intensity interferometry

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

Applications: Stellar Microlensing



STELLAR MASS



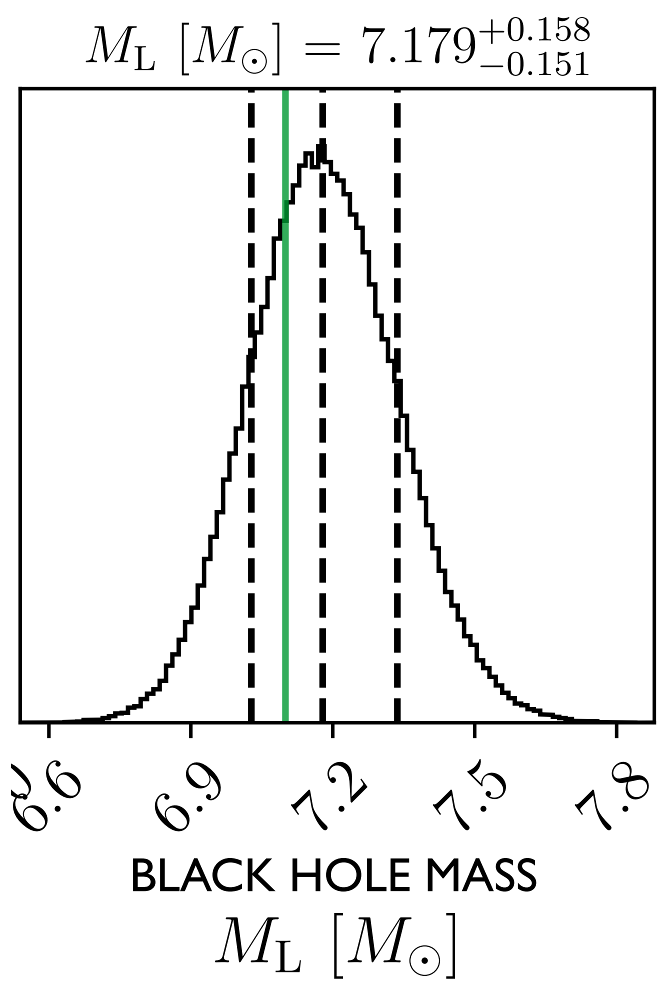
$$\theta_E = \sqrt{\frac{4GM_L}{D_L}\frac{D_{LS}}{D_S}} \sim 3\,\mathrm{mas}\sqrt{\frac{M_L}{M_\odot}\frac{\mathrm{kpc}}{D_L}}$$

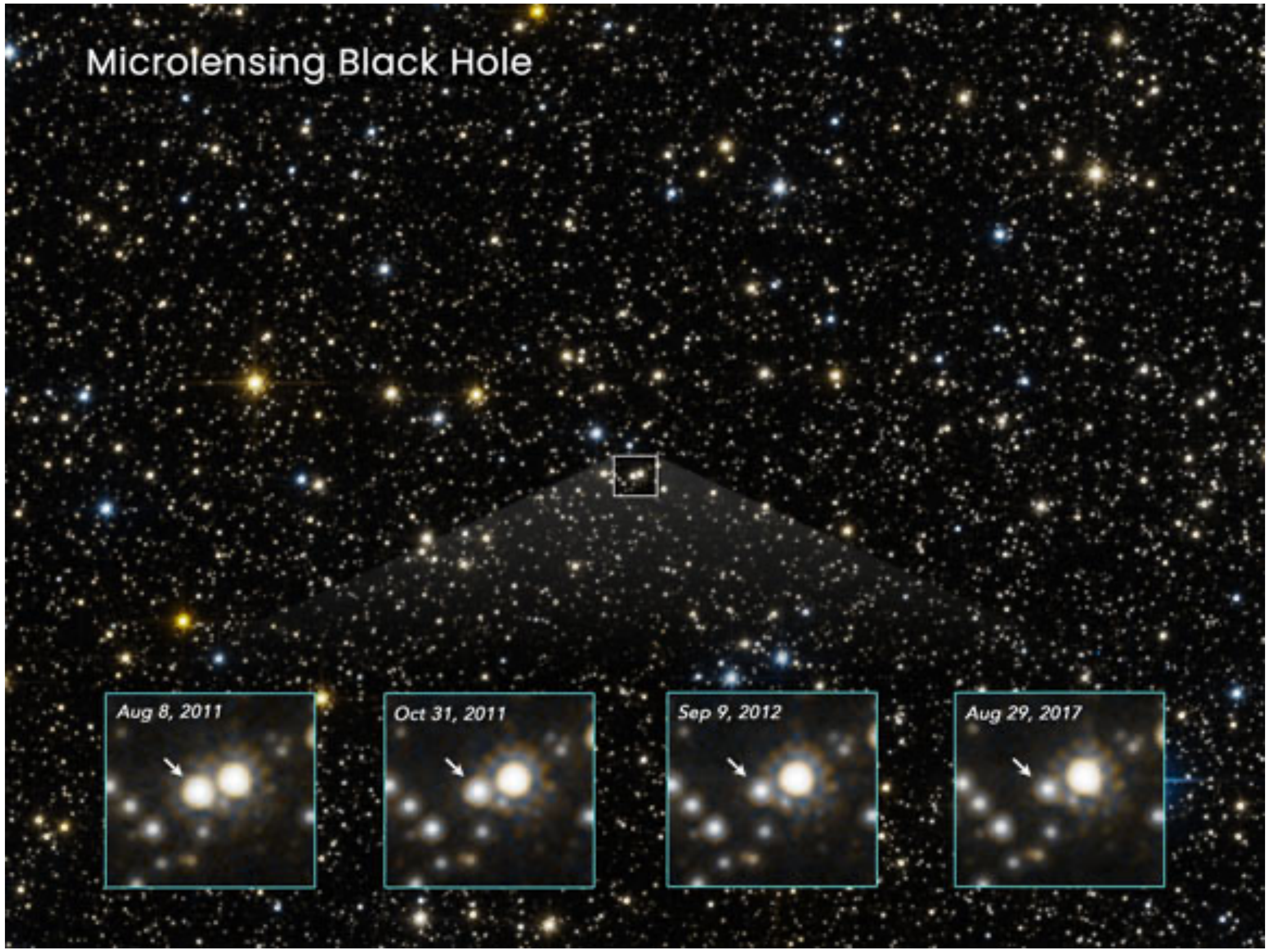
- Determine poorly known stellar separations 10µas within only two observing nights and two baselines.

- 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



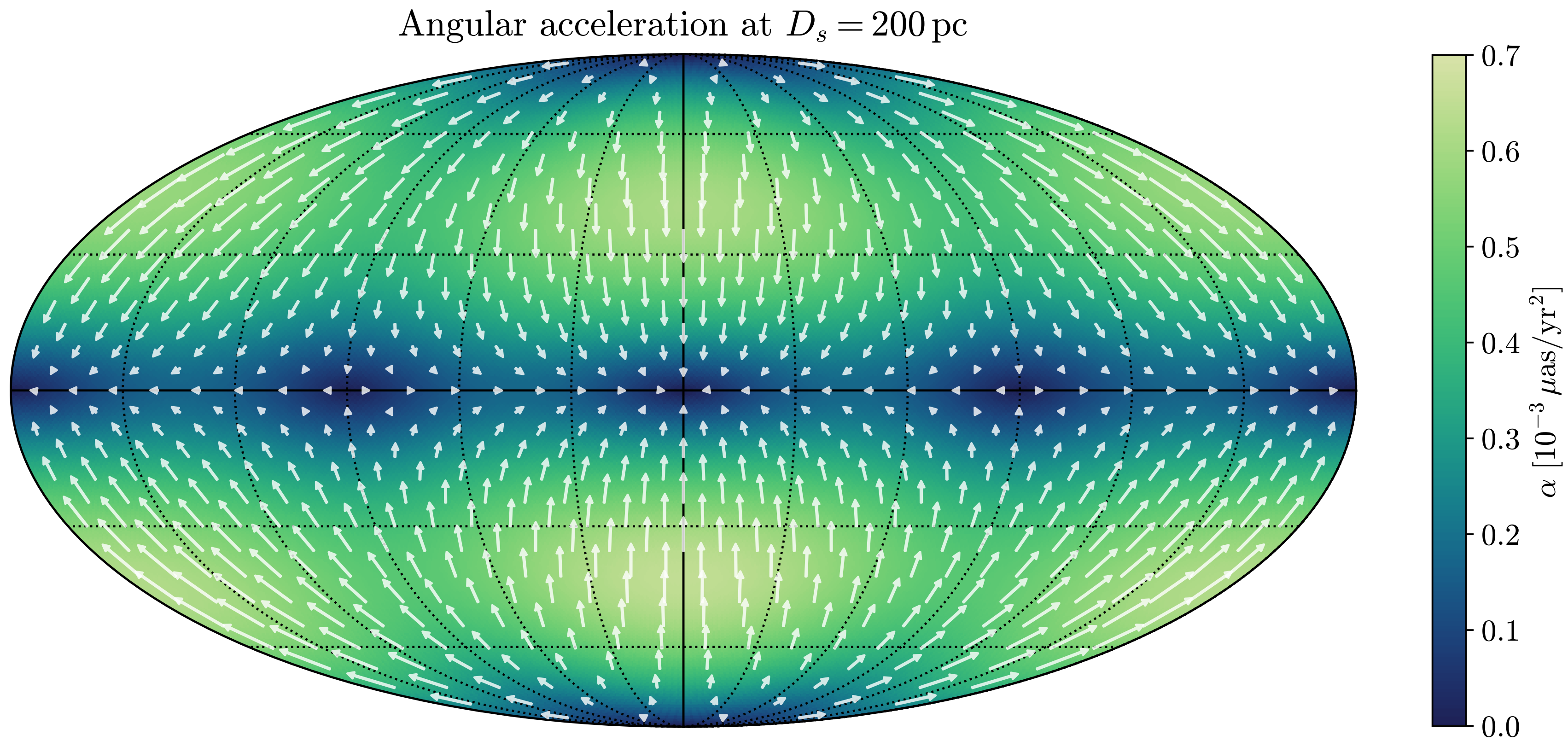


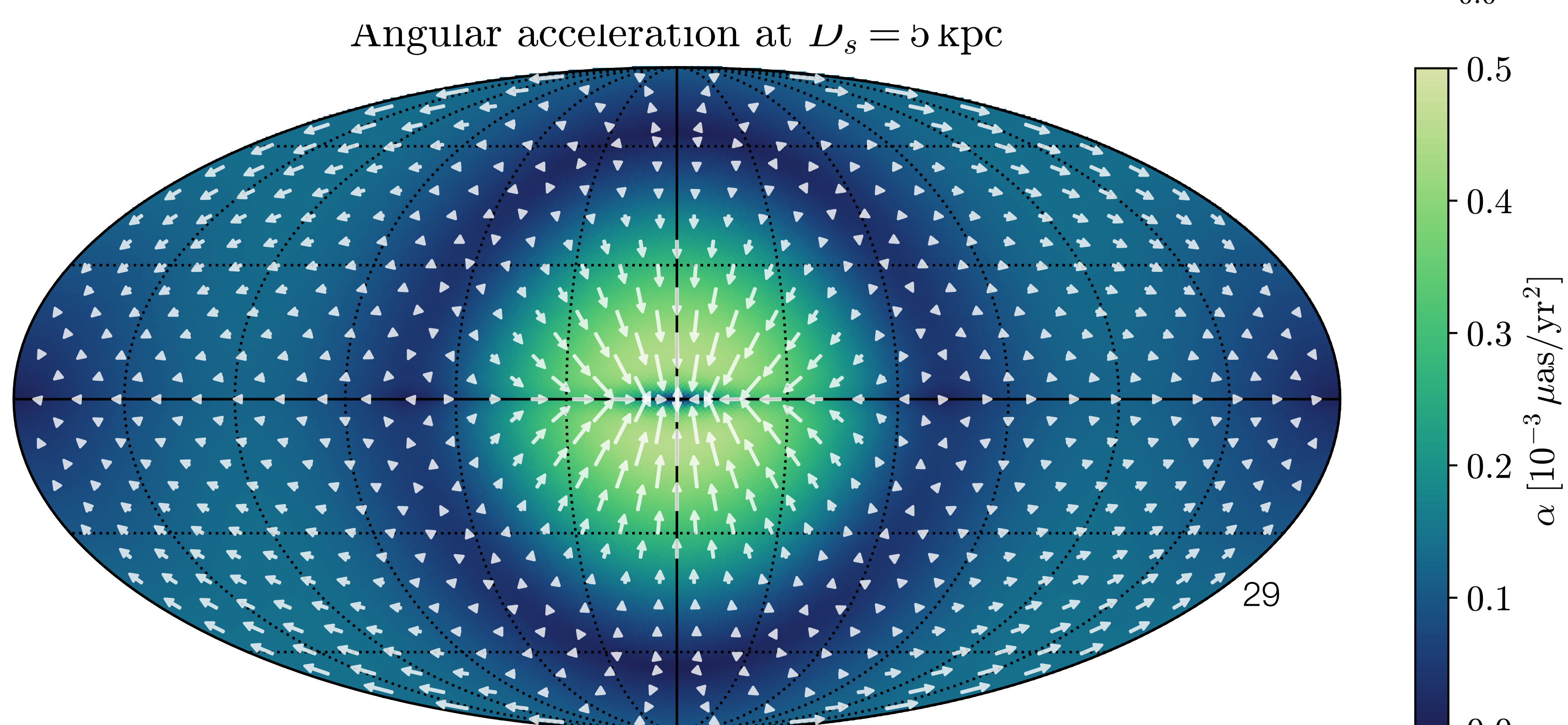
- Mock data set of six relative separation measurements over two years during the closes approach of the two images of MOA-2011-BLG-191/OGLE-2011-BLG-0462
- Determine black hole mass to **1.7% precision:** compare to 18% using HST astrometry

[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



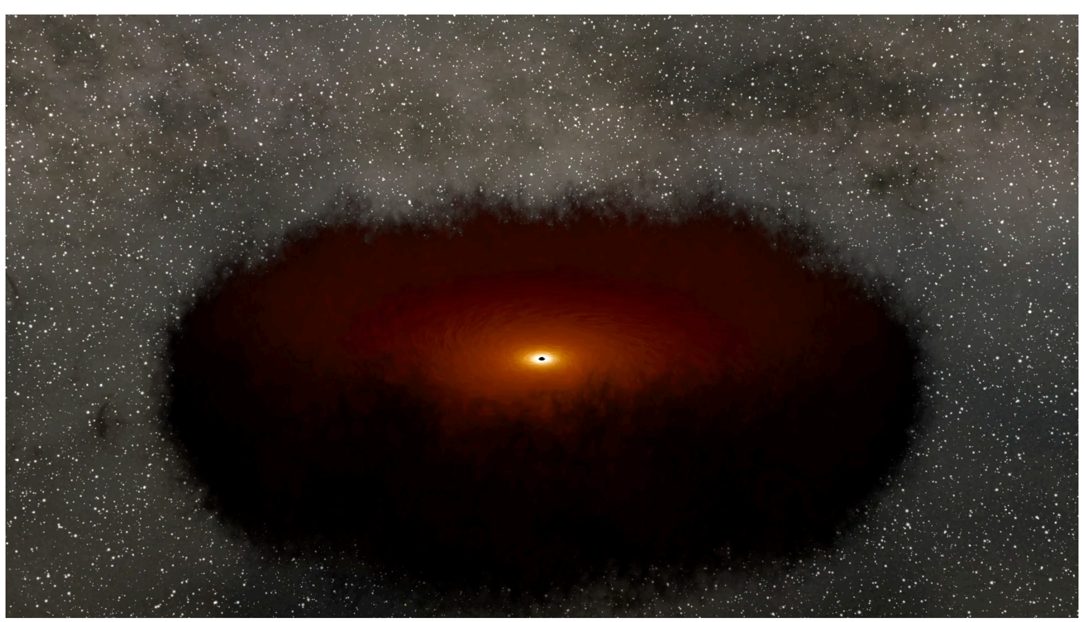


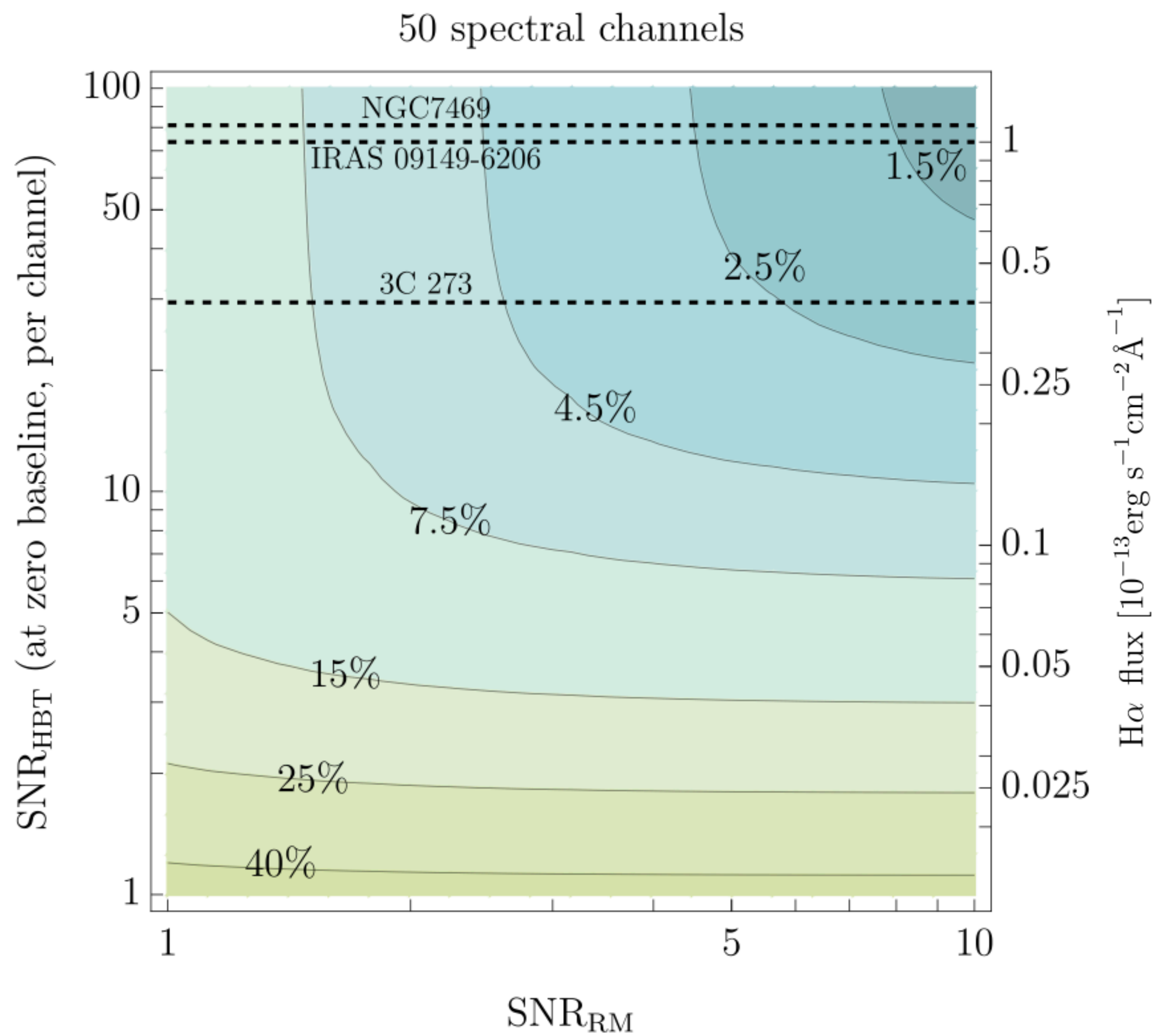
[Galanis, Van Tilburg, **MB**, Weiner, 2307.06989]

Distance or H_0 error per AGN

(no path extension necessary)

CTA-like array with spectroscopic splitting and improved timing can measure percent level distances to AGNs





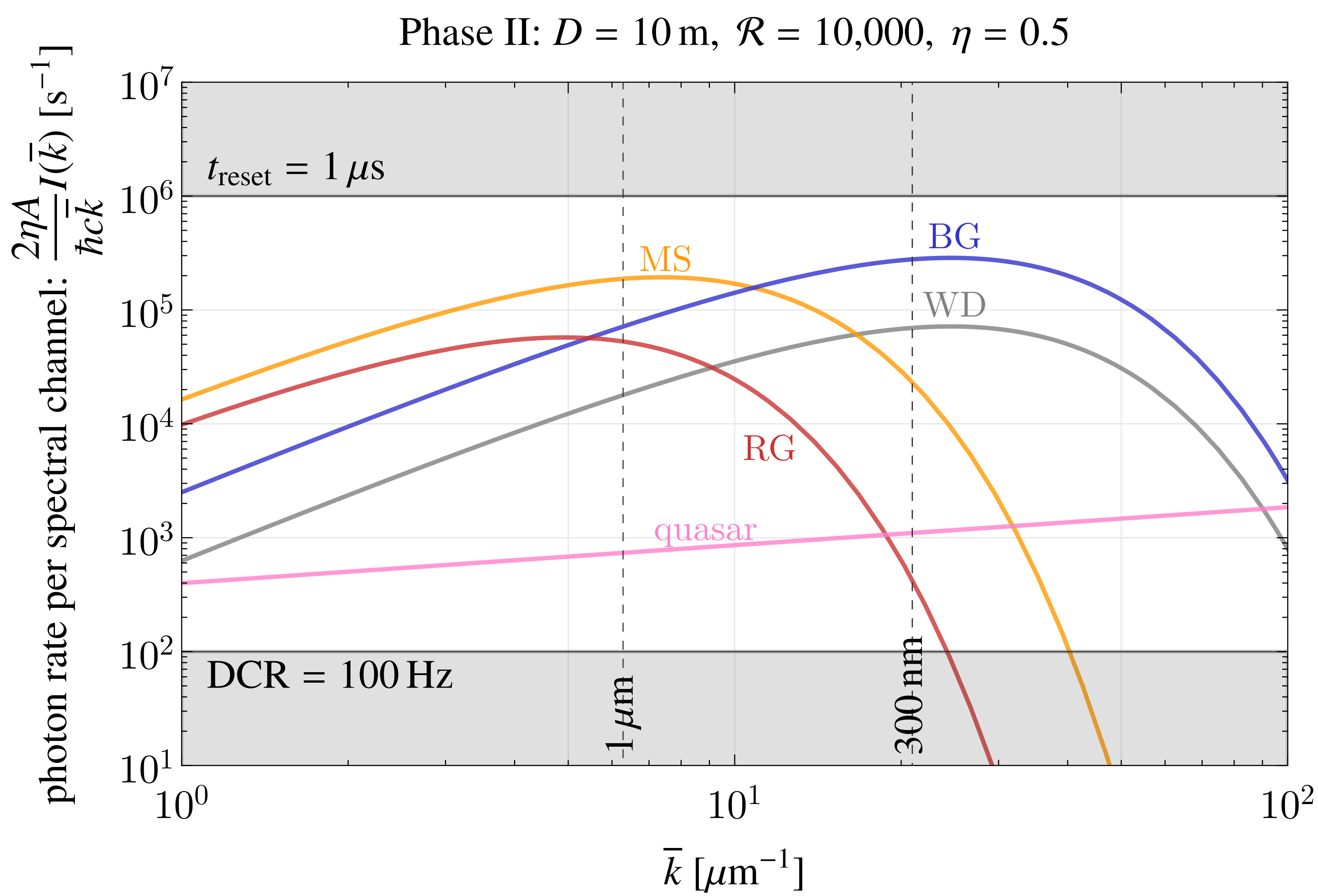
[N. Dalal, M. Galanis, C. Gammie, S. Gralla, N. Murray 2403.15903]

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 precision

Photodetector Requirements



Detector requirements:

- Minimize timing error in detector and readout
- Maximize multichannel readout with narrow band spectral splitting
- Good efficiency but close to 1 not crucial
- Large enough area to focus within atmospheric error

$$\mathrm{SNR} \sim \epsilon_T \sqrt{N_{\mathrm{coincident}}}$$
$$\sim \tau_{\mathrm{coh}} \sqrt{\frac{t_{\mathrm{obs}}}{\sigma_t}} D^2 \times \mathrm{flux}$$

WD @ 10 pc

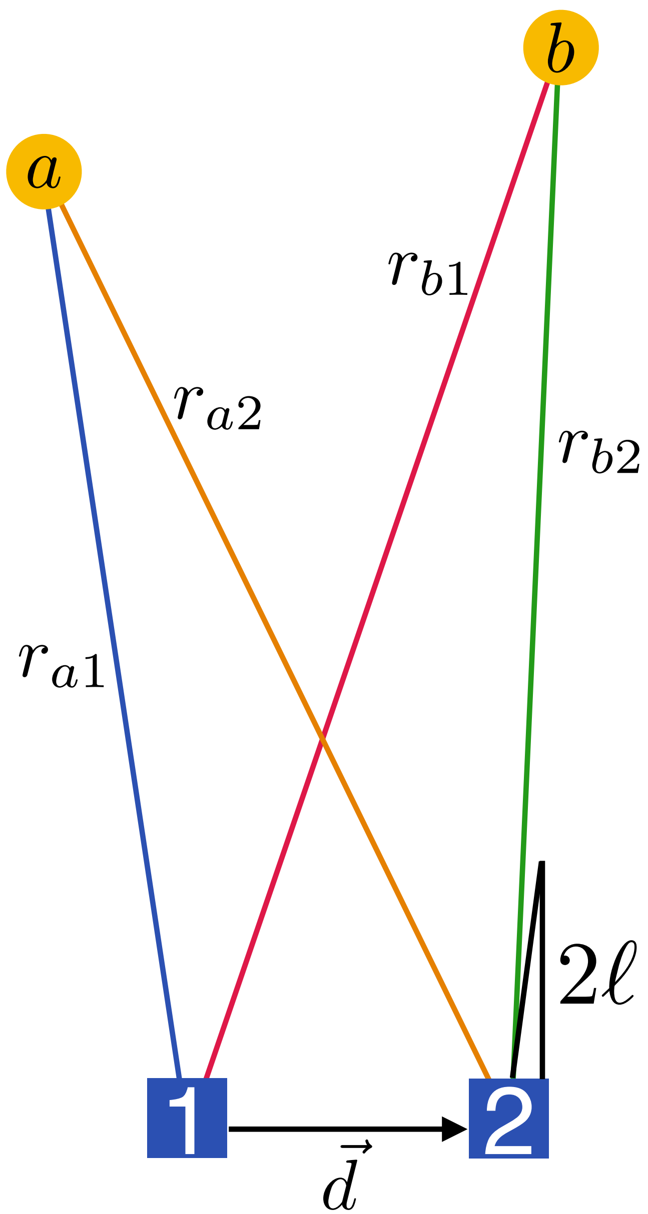
Sun-like MS @ 100 pc

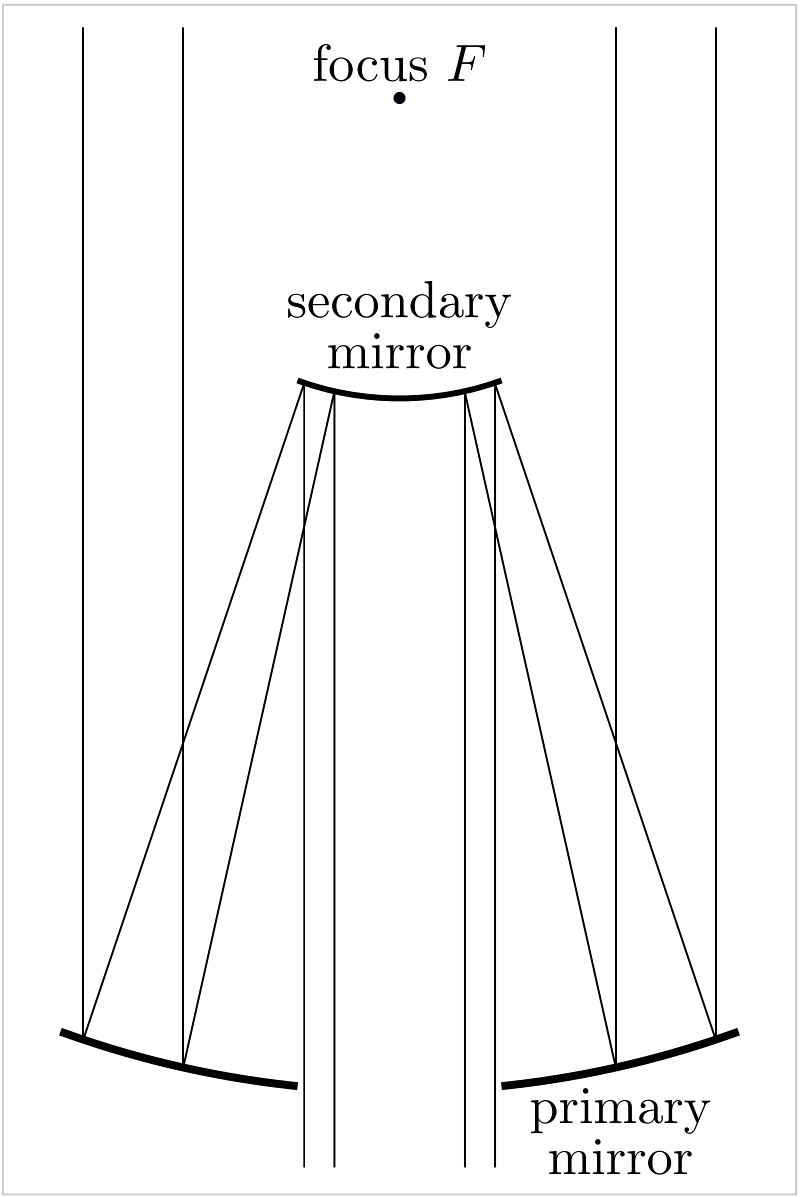
RG/BG @ 5 kpc

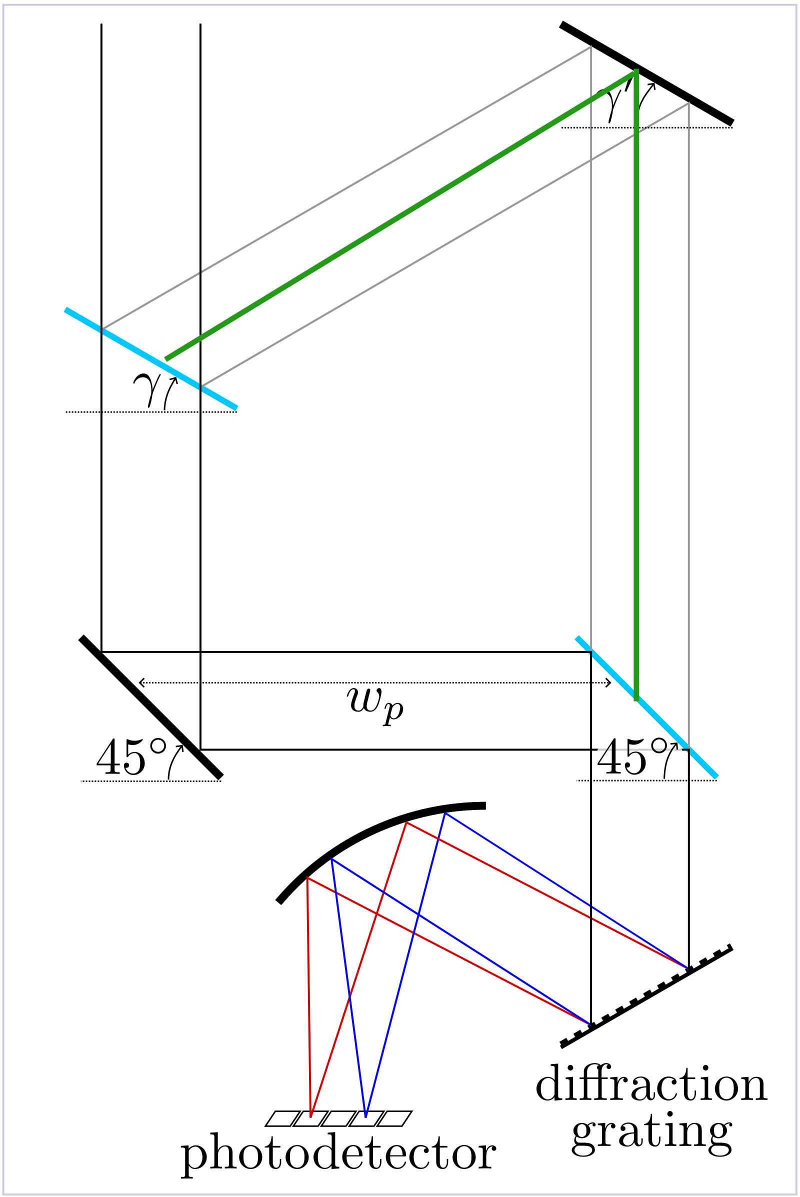
bright quasar

[Marios Galanis, Ken Van Tilburg, Masha Baryakhtar, and Neal Weiner, arXiv preprint 2307.06989]

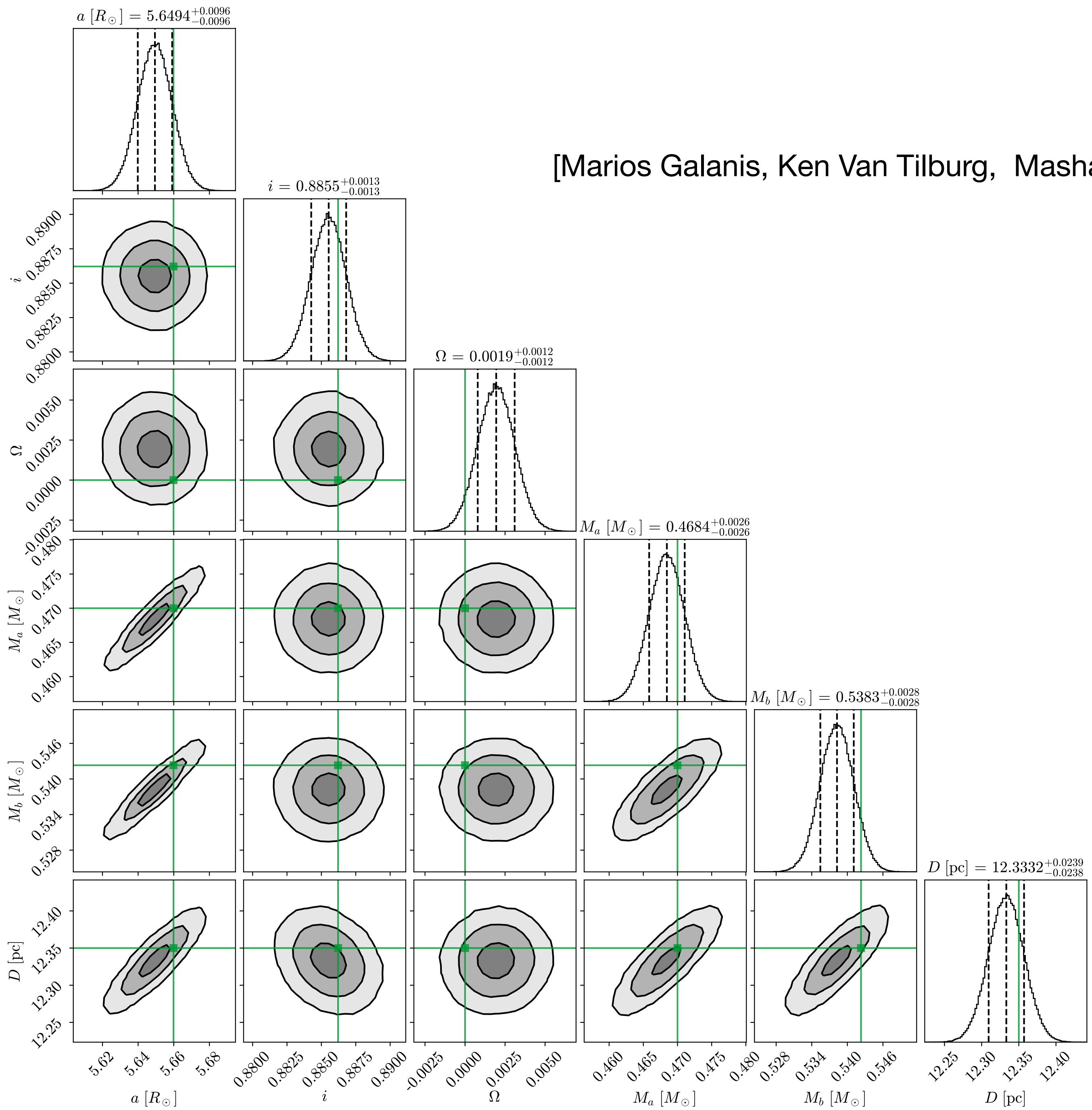
Extended-Path Intensity Correlation



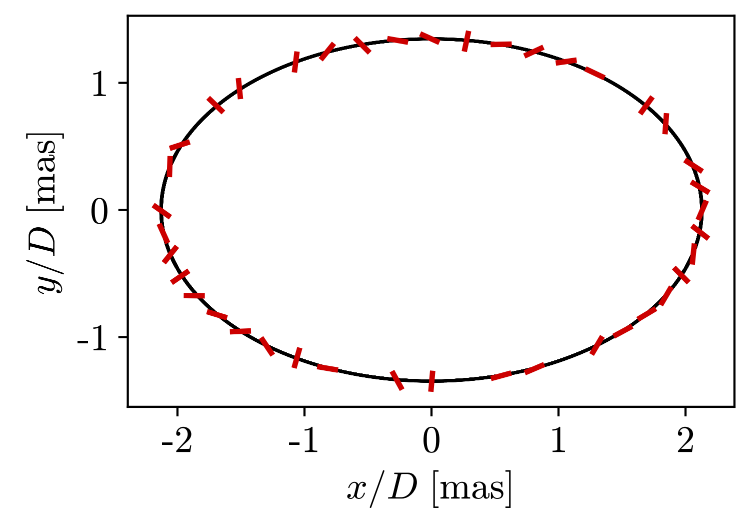


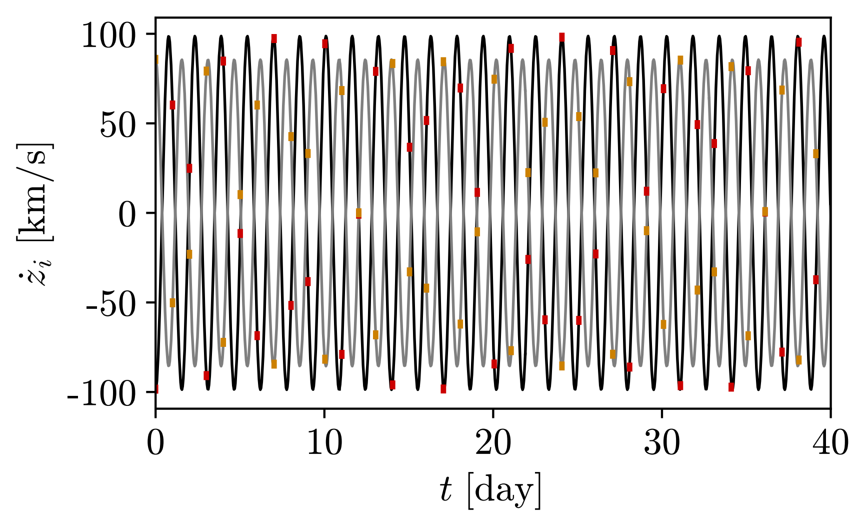


Applications: Binary Orbits



[Marios Galanis, Ken Van Tilburg, Masha Baryakhtar, and Neal Weiner, arXiv preprint 2307.06989]

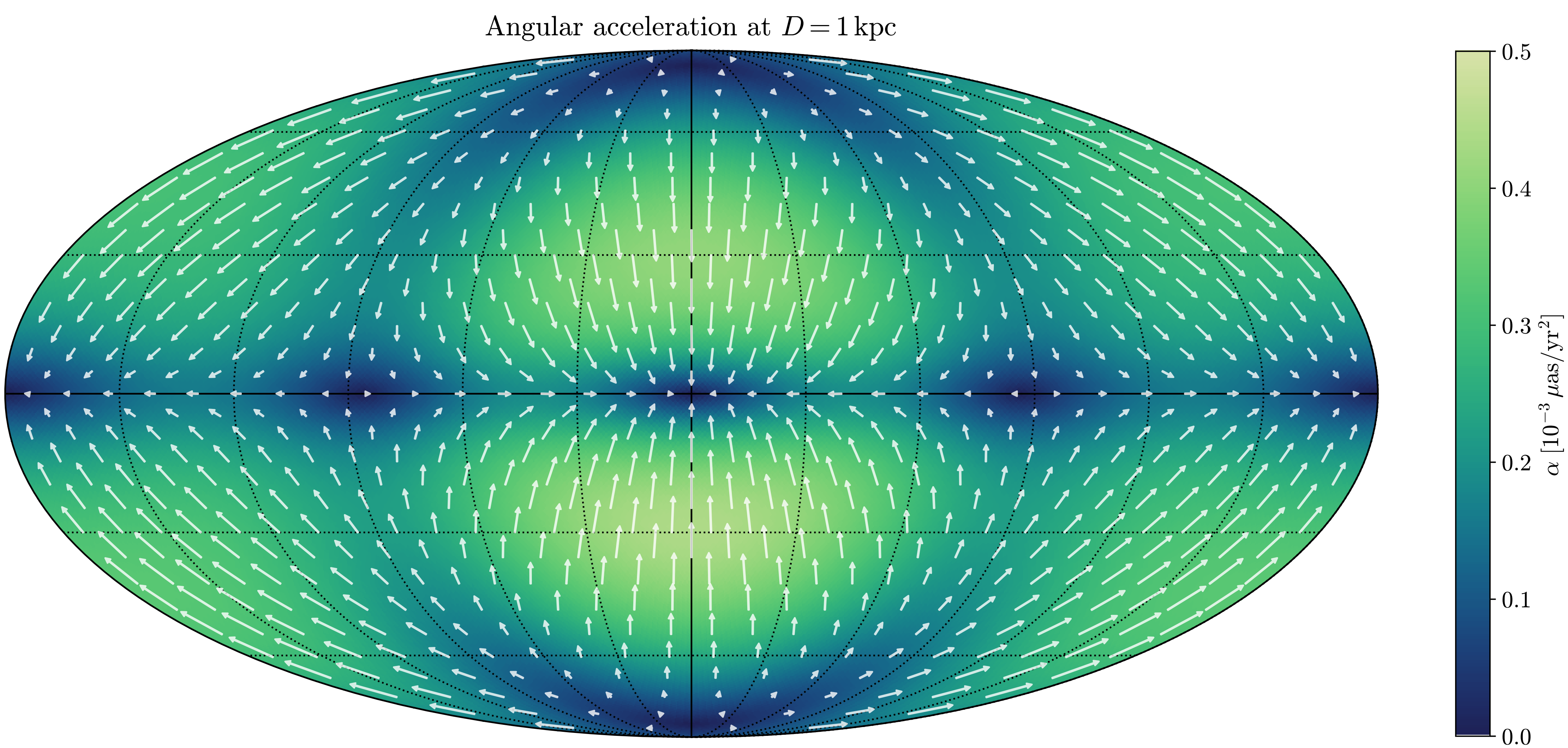




- .An astrometric precision per observation epoch of 3 × 10−13 achievable on bright binaries yielding component masses with a fractional precision at the 10−4 level
- Conceivably start to measure the mass loss rate a WR star at 10−4 M⊙/yr!

Applications: Galactic Accelerations

[Marios Galanis, Ken Van Tilburg, Masha Baryakhtar, and Neal Weiner, arXiv preprint 2307.06989]



- For a futuristic EPIC intensity interferometer, could reach nas/yr^2 for monthly observations over 30 yrs