Extended Path Intensity Correlation Astrometry

to appear w/
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University of Washington

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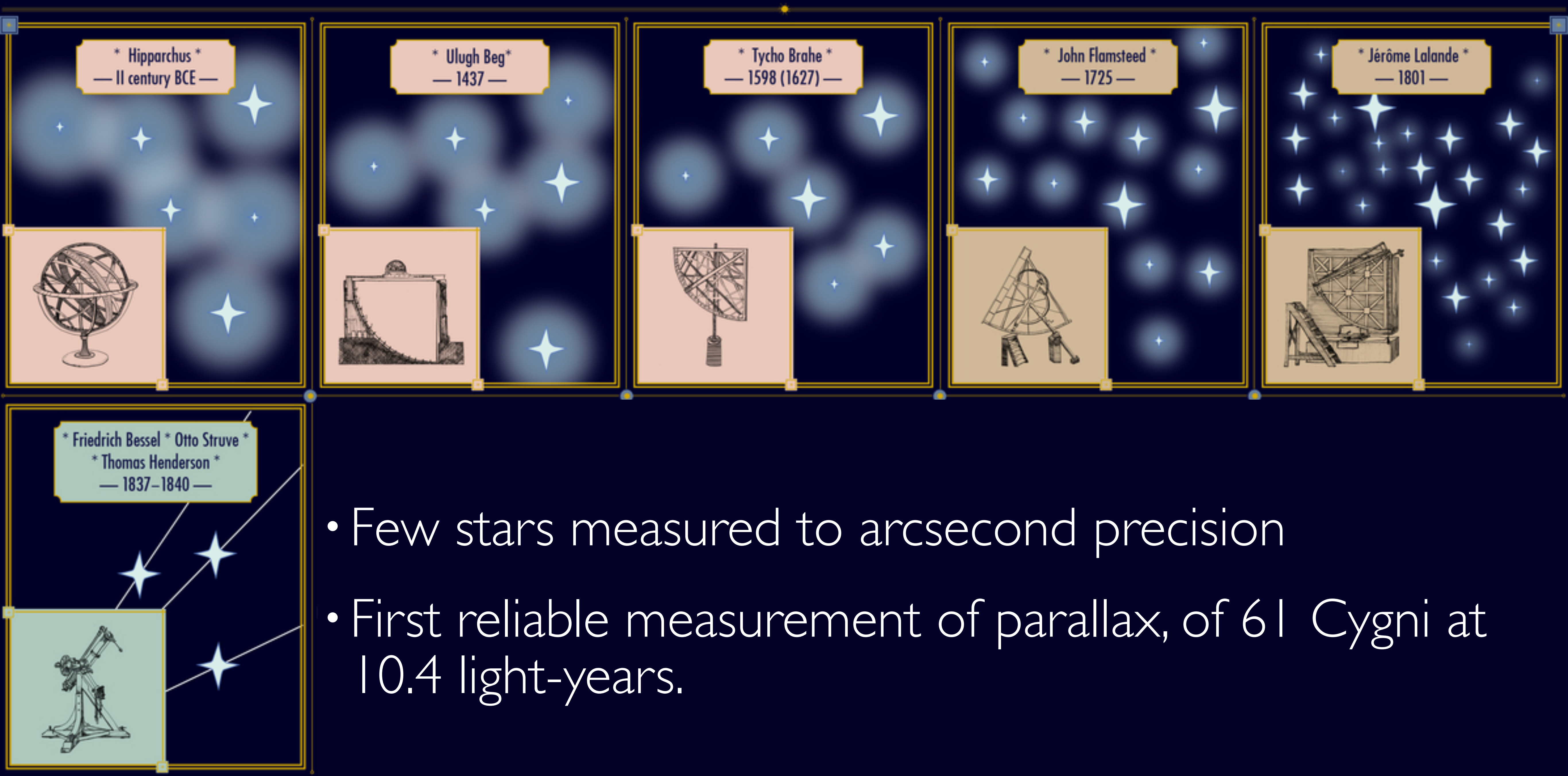
➔ ASTROMETRY THROUGH THE AGES

- 850 stars
- ~one degree precision (size of full moon)
- Comparing with data from his predecessors, Timocharis and Aristillus, discovered the precession of the Earth

→ ASTROMETRY THROUGH THE AGES

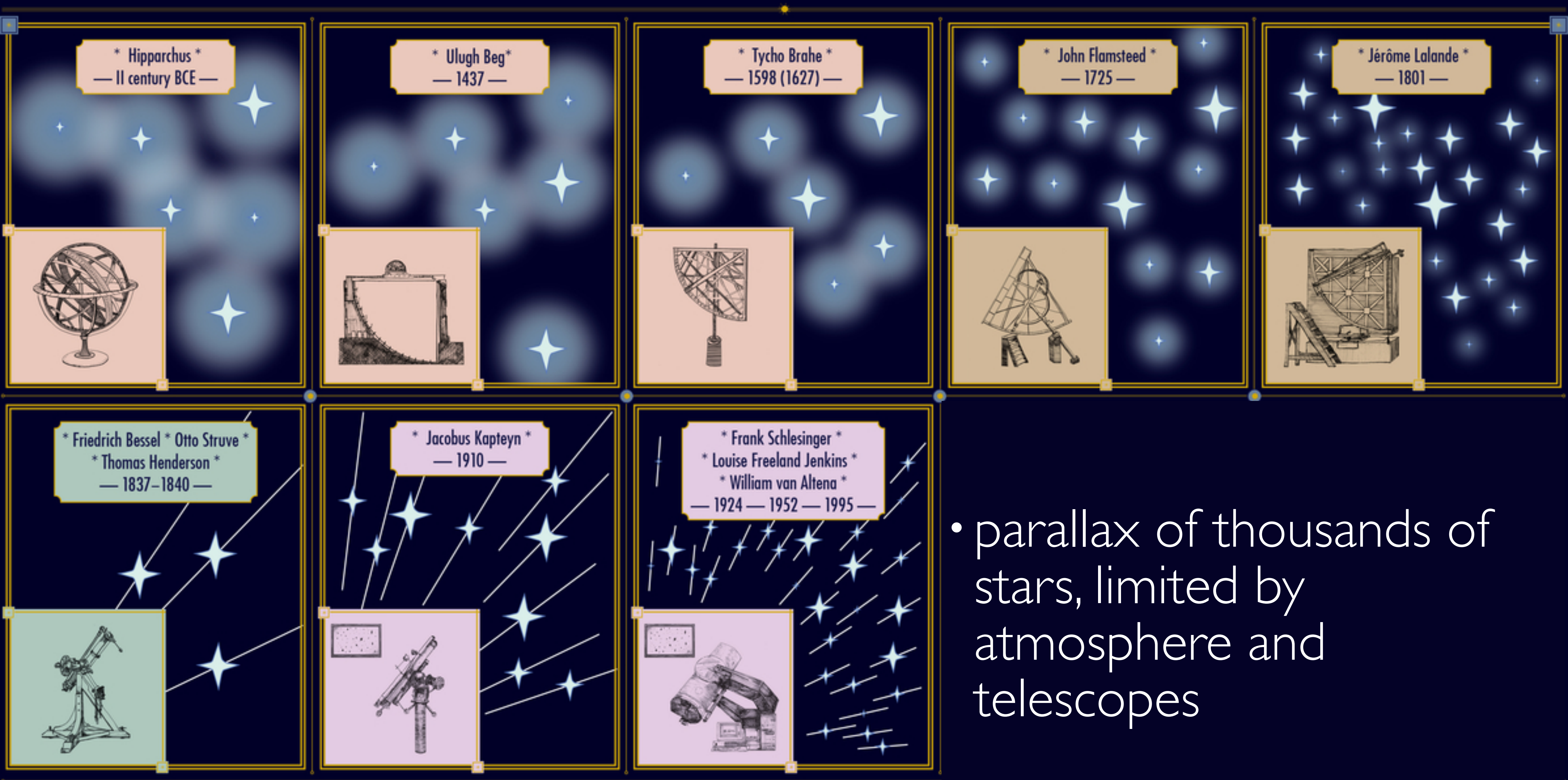
- 1000 stars
- ~one arcminute precision (size of Venus)
- Led Kepler to planetary laws of motion and heliocentric system

→ ASTROMETRY THROUGH THE AGES



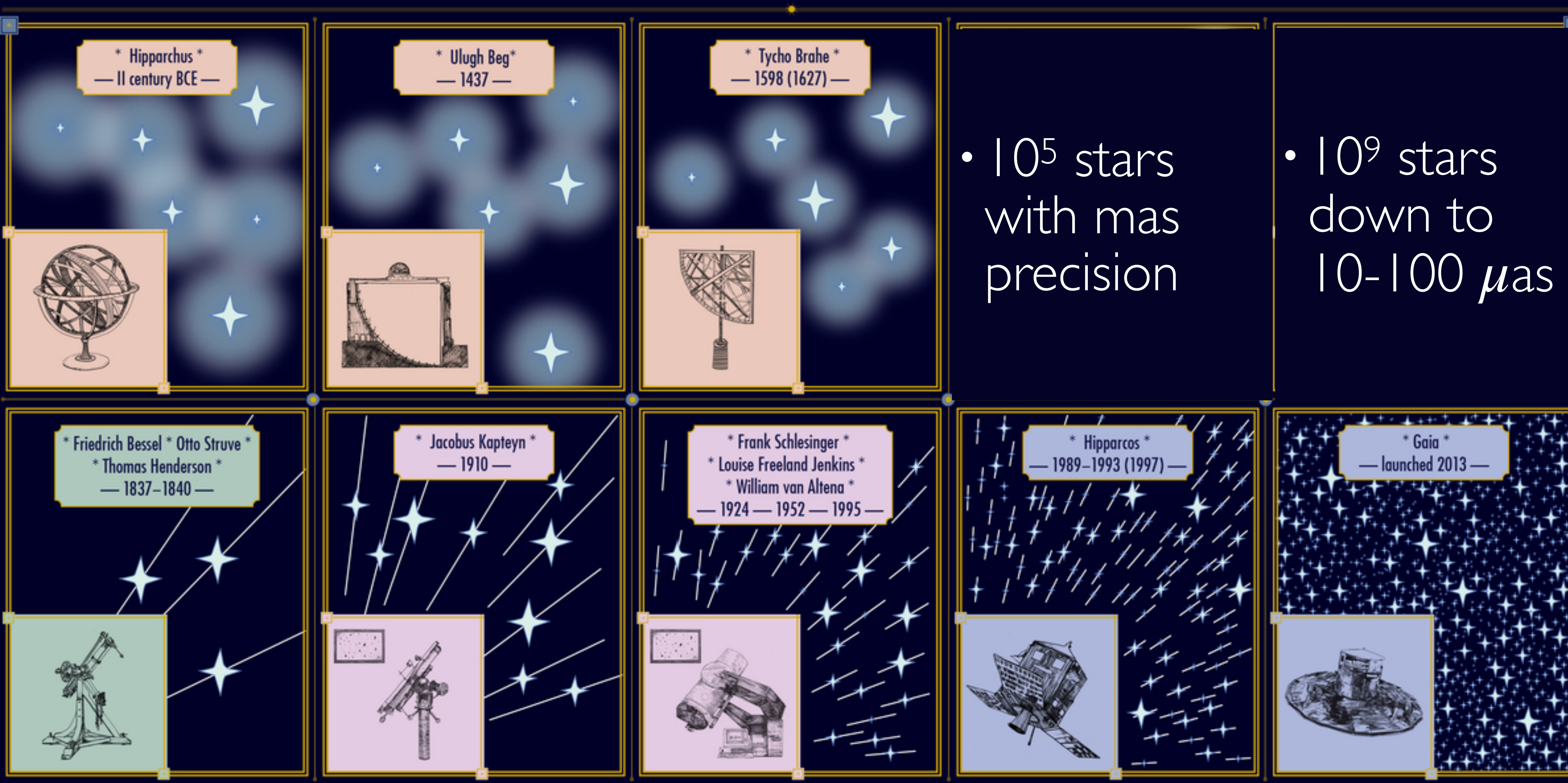
- Few stars measured to arcsecond precision
- First reliable measurement of parallax, of 61 Cygni at 10.4 light-years.

→ ASTROMETRY THROUGH THE AGES



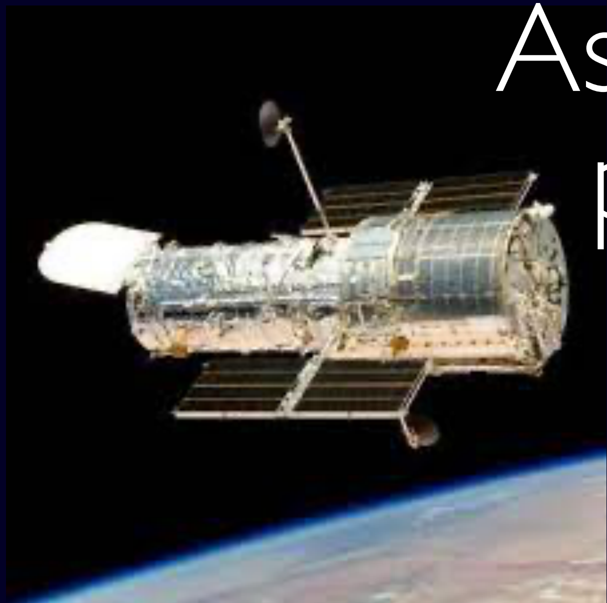
- parallax of thousands of stars, limited by atmosphere and telescopes

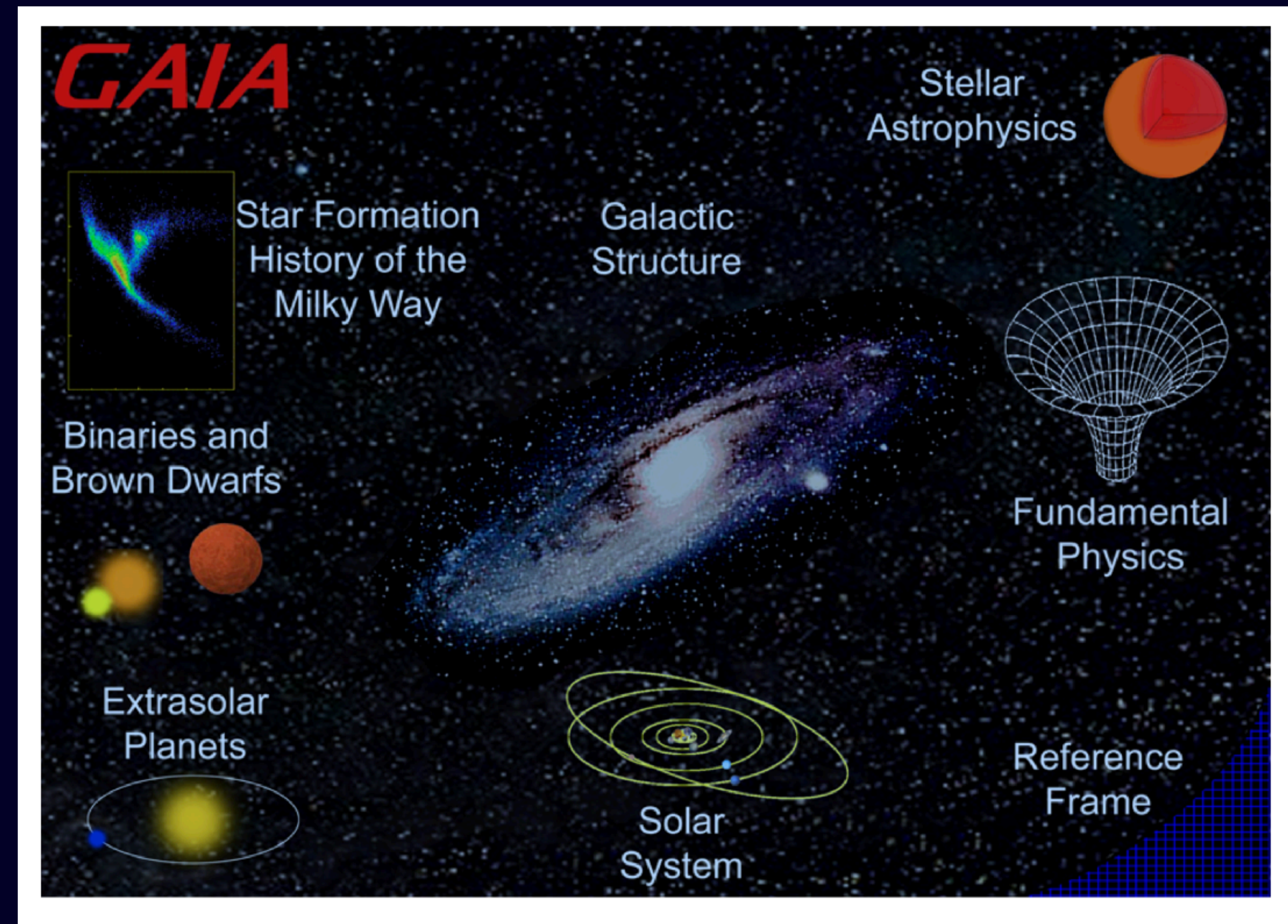
→ ASTROMETRY THROUGH THE AGES



- 10^5 stars with mas precision
- 10^9 stars down to 10-100 μas

Astrometry promises to





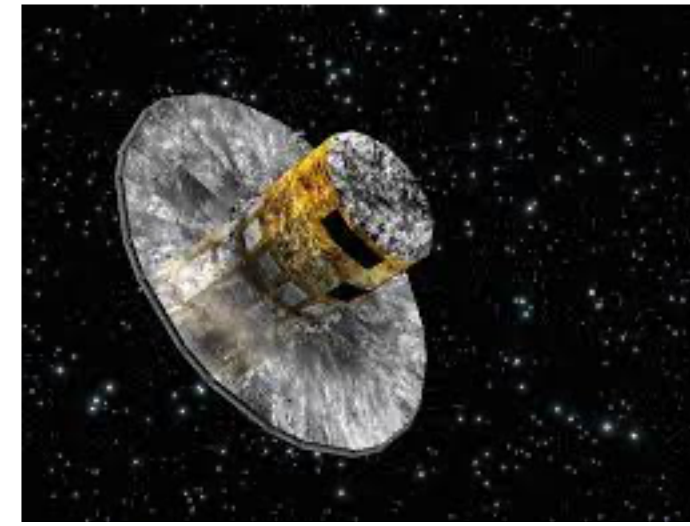
- Discover exoplanets
- Measure microlensing of stars to measure stellar masses and find dark structures
- Map stellar accelerations and the gravitational potential of the galaxy
- Reveal the history of the Milky Way
- Measure stellar orbits around our galactic black hole
- Provide new rungs in the cosmic distance ladder
- ….

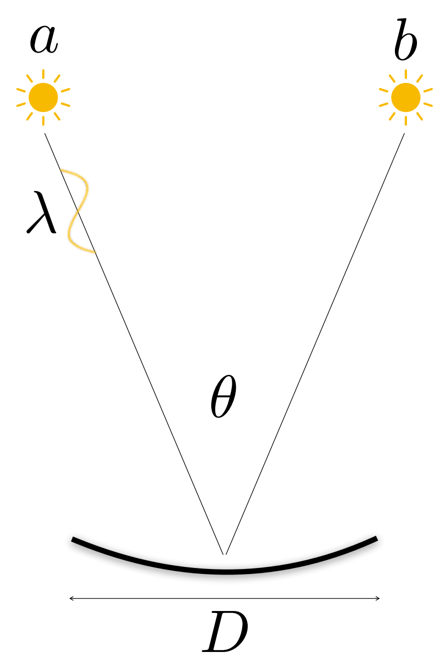
Outline

- Precision Astrometry
- Intensity interferometry
- Science cases

Measuring angles on the sky

Direct Imaging





Angular resolution limited by atmosphere, telescope size

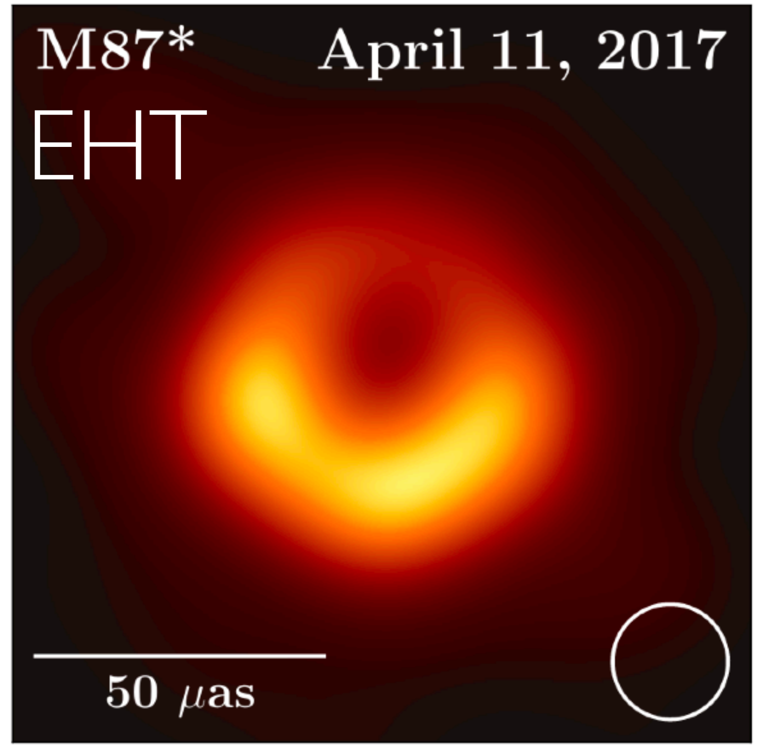
$$\sigma_{\theta_{\rm res}}^{Gaia} \sim \frac{\lambda}{D}$$
$$\approx 0.4 \text{ arcsec} \approx 10^{-6} \text{ rad}$$

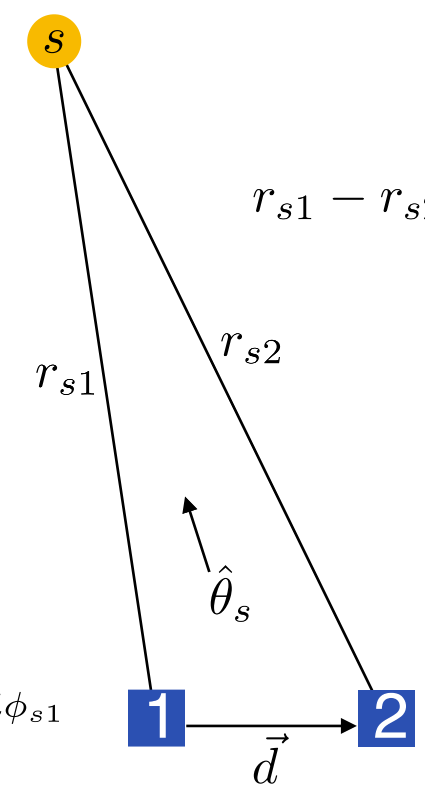
$$\sigma_{\theta} \sim \frac{\lambda}{D} \times \max\left\{\frac{1}{\sqrt{N}}, \epsilon_{\rm PSF}\right\}$$

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

Measuring angles on the sky

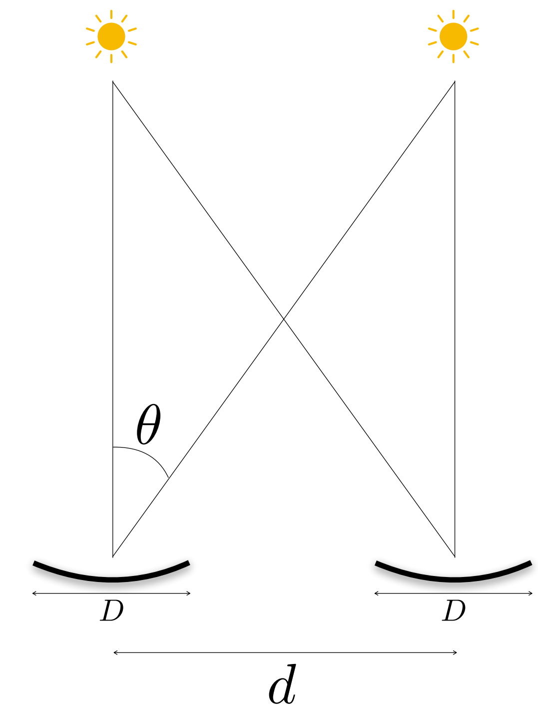
Amplitude interferometry





$$r_{s1} - r_{s2} \simeq -\hat{\theta}_s \cdot \vec{d}$$

$$E_1 = E_s e^{i\phi_{s1}} \qquad E_2 = E_s e^{i\phi_{s2}}$$



$$\sigma_{\theta_{\rm res}} \sim \frac{\lambda}{d}$$

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

Angular resolution limited by ability to record amplitude: long wavelengths

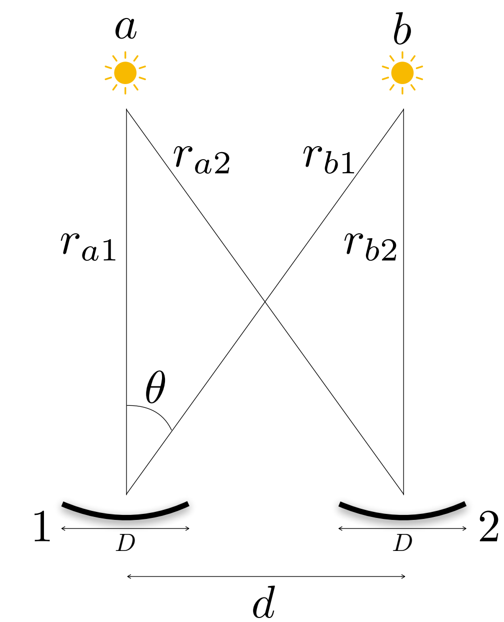
Measuring angles on the sky

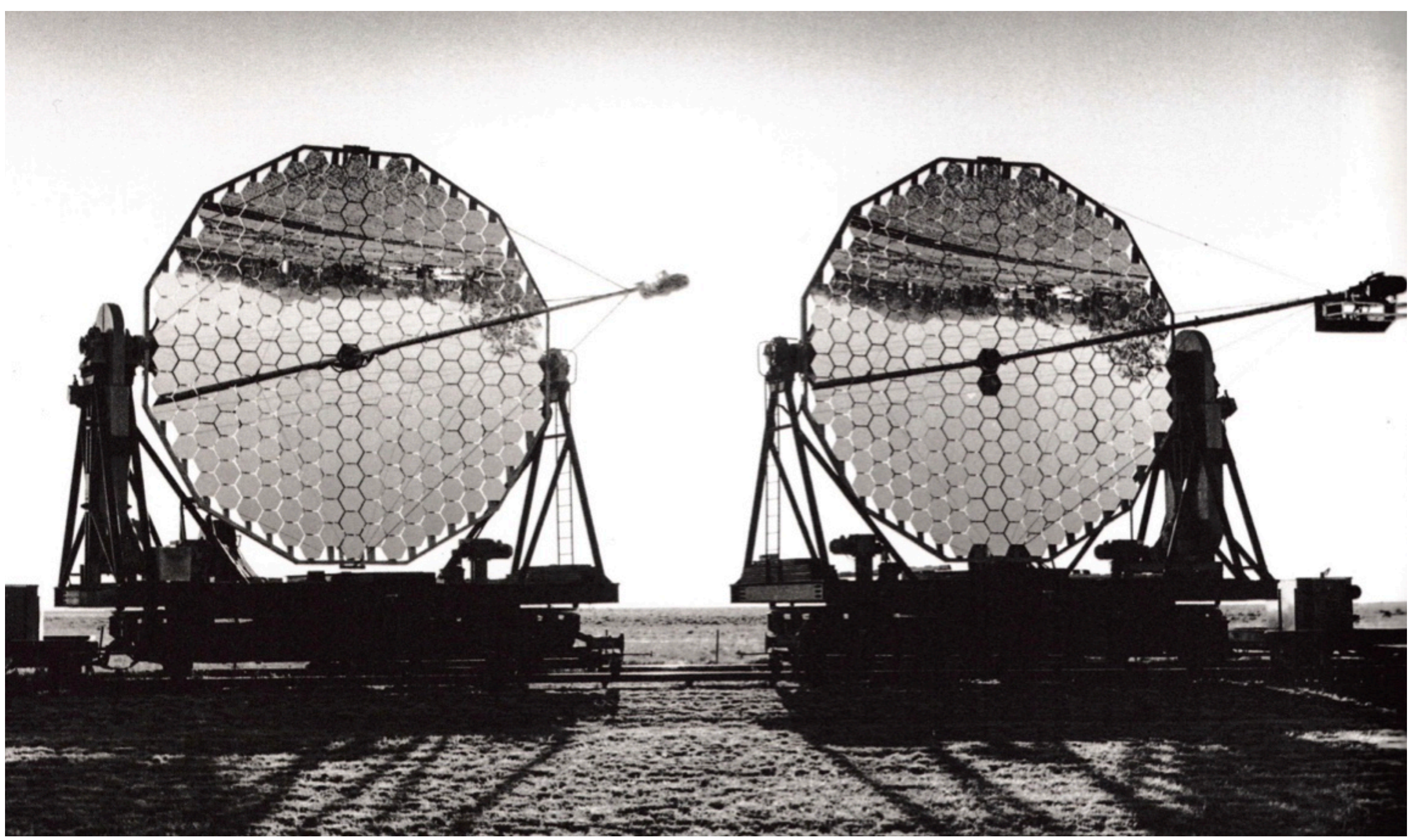
Intensity Interferometry

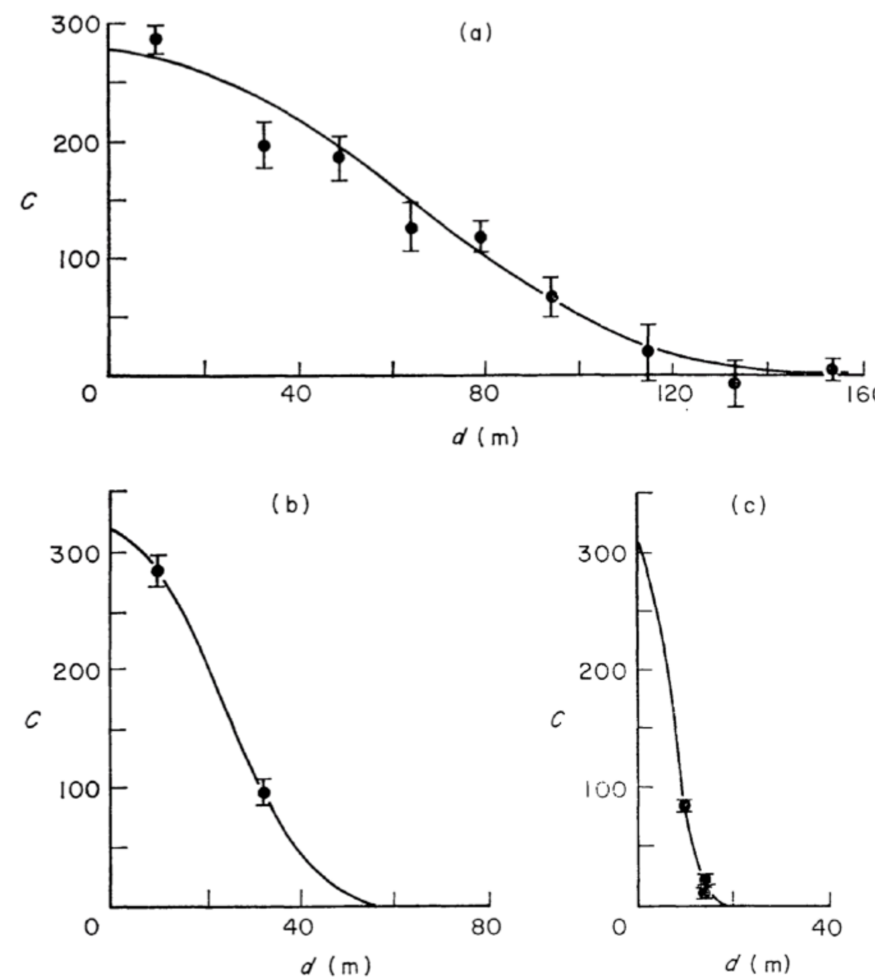
Record photon counts, not electric fields

Baseline set by telescope separation: can be 100s of meters to 1000s of km

$$\sigma_\theta \sim \frac{\lambda}{d} \times \frac{1}{\mathrm{SNR}}$$





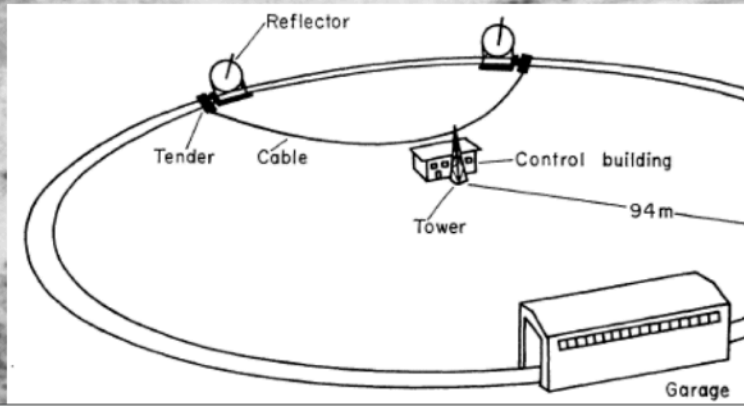


Intensity interferometry … the early days

Narrabri observatory

with its circular railway track

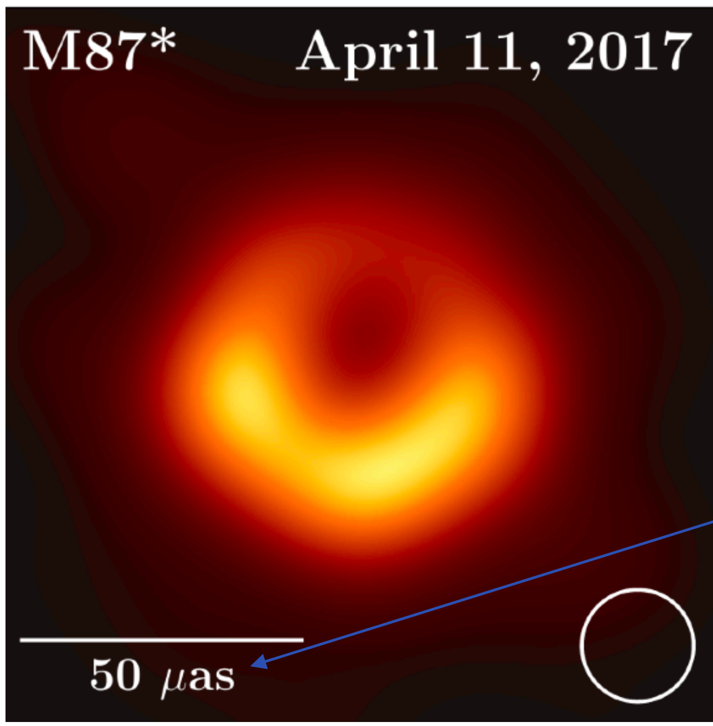
R.Hanbury Brown: *BOFFIN. A Personal Story of the Early Days of Radar, Radio Astronomy and Quantum Optics* (1991)



Measuring angles on the sky

Intensity Interferometry

EHT



Star number	Star name	Type	Zero-baseline correlation $c_N \pm \sigma$	Angular diameter $\times 10^{-3}$ sec of arc $\theta_{UD} \pm \sigma$	$\theta_{LD} \pm \sigma$	Temperature $[T_e(F) \pm \sigma]$/K
472	α Eri	B 3 (Vp)	0·98 ± 0·05	1·85 ± 0·07	1·92 ± 0·07	13 700 ± 600
1713	β Ori	B 8 (Ia)	0·98 ± 0·08	2·43 ± 0·05	2·55 ± 0·05	11 500 ± 700
1790	γ Ori	B 2 (III)	1·03 ± 0·07	0·70 ± 0·04	0·72 ± 0·04	20 800 ± 1300
1903	ε Ori	B O (Ia)	0·86 ± 0·07	0·67 ± 0·04	0·69 ± 0·04	24 500 ± 2000
1948	ζ Ori	O 9·5 (Ib)	0·60 ± 0·06	0·47 ± 0·04	0·48 ± 0·04	26 100 ± 2200
2004	κ Ori	B 0·5 (Ia)	1·18 ± 0·09	0·44 ± 0·03	0·45 ± 0·03	30 400 ± 2000
2294	β CMa	B 1 (II–III)	1·07 ± 0·08	0·50 ± 0·03	0·52 ± 0·03	25 300 ± 1500
2326	α Car	F 0 (Ib–II)	0·75 ± 0·22	6·1 ± 0·7	6·6 ± 0·8	7500 ± 250
2421	γ Gem	A 0 (IV)	1·17 ± 0·09	1·32 ± 0·09	1·39 ± 0·09	9600 ± 500
2491	α CMa	A 1 (V)	0·91 ± 0·06	5·60 ± 0·15	5·89 ± 0·16	10 250 ± 150
2618	ε CMa	B 2 (II)	0·89 ± 0·06	0·77 ± 0·05	0·80 ± 0·05	20 800 ± 1300
2693	δ CMa	F 8 (Ia)	0·93 ± 0·18	3·29 ± 0·46	3·60 ± 0·50	— —
2827	η CMa	B 5 (Ia)	0·99 ± 0·09	0·72 ± 0·06	0·75 ± 0·06	14 200 ± 1300
2943	α CMi	F 5 (IV–V)	0·98 ± 0·10	5·10 ± 0·16	5·50 ± 0·17	6500 ± 200
3165	ζ Pup	O 5 (f)	1·04 ± 0·08	0·41 ± 0·03	0·42 ± 0·03	30 700 ± 2500
3207	γ^2 Vel	WC 8 + O 9 (I)	—	0·43 ± 0·05	0·44 ± 0·05	29 000 ± 3000
3685	β Car	A 1 (IV)	1·01 ± 0·06	1·51 ± 0·07	1·59 ± 0·07	9500 ± 350
3982	α Leo	B 7 (V)	1·12 ± 0·07	1·32 ± 0·06	1·37 ± 0·06	12 700 ± 800
4534	β Leo	A 3 (V)	1·17 ± 0·10	1·25 ± 0·09	1·33 ± 0·10	9050 ± 450
4662	γ Crv	B 8 (III)	0·97 ± 0·10	0·72 ± 0·06	0·75 ± 0·06	13 100 ± 1200
4853	β Cru	B 0·5 (III)	0·88 ± 0·03	0·702 ± 0·022	0·722 ± 0·023	27 900 ± 1200
5056	α Vir	B 1 (IV)	—	0·85 ± 0·04	0·87 ± 0·04	22 400 ± 1000
5132	ε Cen	B 1 (III)	1·02 ± 0·07	0·47 ± 0·03	0·48 ± 0·03	26 000 ± 1800
5953	δ Sco	B 0·5 (IV)	0·75 ± 0·07	0·45 ± 0·04	0·46 ± 0·04	— —
6175	ζ Oph	O 9·5 (V)	1·01 ± 0·12	0·50 ± 0·05	0·51 ± 0·05	— —
6556	α Oph	A 5 (III)	0·94 ± 0·09	1·53 ± 0·12	1·63 ± 0·13	8150 ± 400
6879	ε Sgr	A 0 (V)	1·02 ± 0·06	1·37 ± 0·06	1·44 ± 0·06	9650 ± 400
7001	α Lyr	A 0 (V)	0·99 ± 0·04	3·08 ± 0·07	3·24 ± 0·07	9250 ± 350
7557	α Aql	A 7 (IV, V)	0·94 ± 0·06	2·78 ± 0·13	2·98 ± 0·14	8250 ± 250
7790	α Pav	B 2·5 (V)	1·01 ± 0·07	0·77 ± 0·05	0·80 ± 0·05	17 100 ± 1400
8425	α Gru	B 7 (IV)	1·11 ± 0·08	0·98 ± 0·07	1·02 ± 0·07	14 800 ± 1200
8728	α PsA	A 3 (V)	1·02 ± 0·08	1·98 ± 0·13	2·10 ± 0·14	9200 ± 500

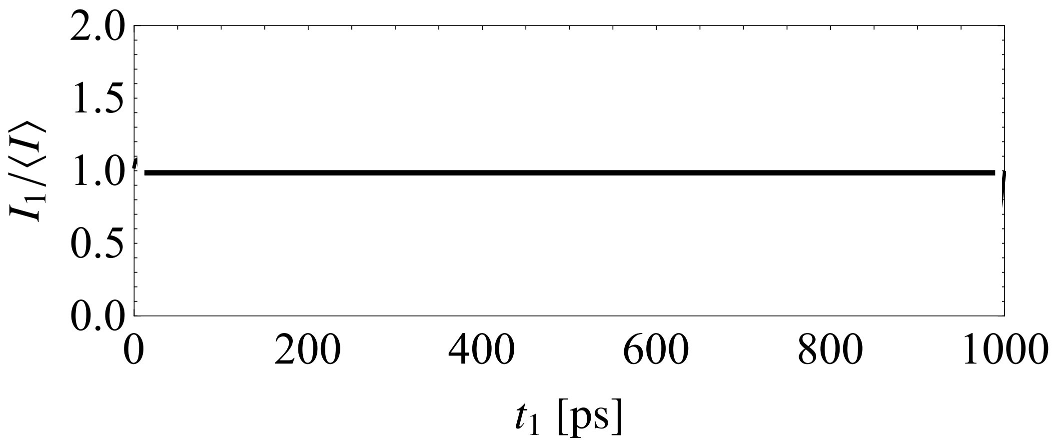
Narrabri II 1965–1974

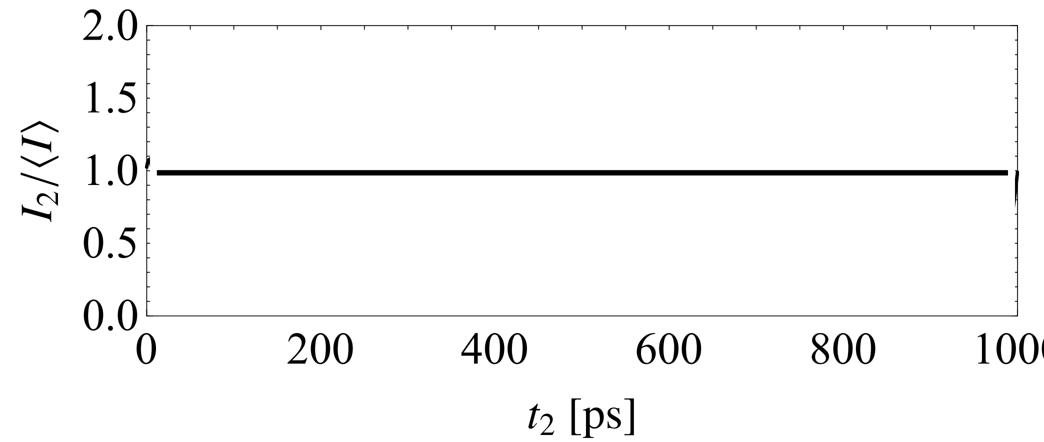
Outline

- Precision Astrometry
- Intensity interferometry
- Science cases

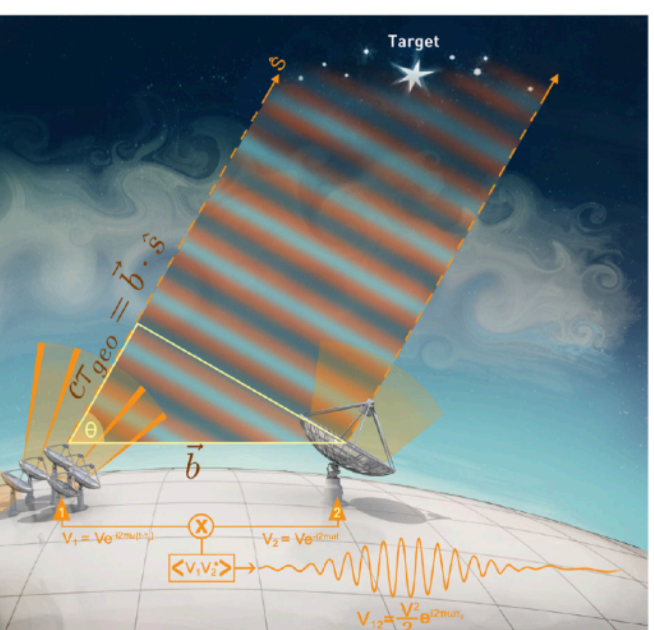
Intensity Interferometry

Second Order Correlations of Light





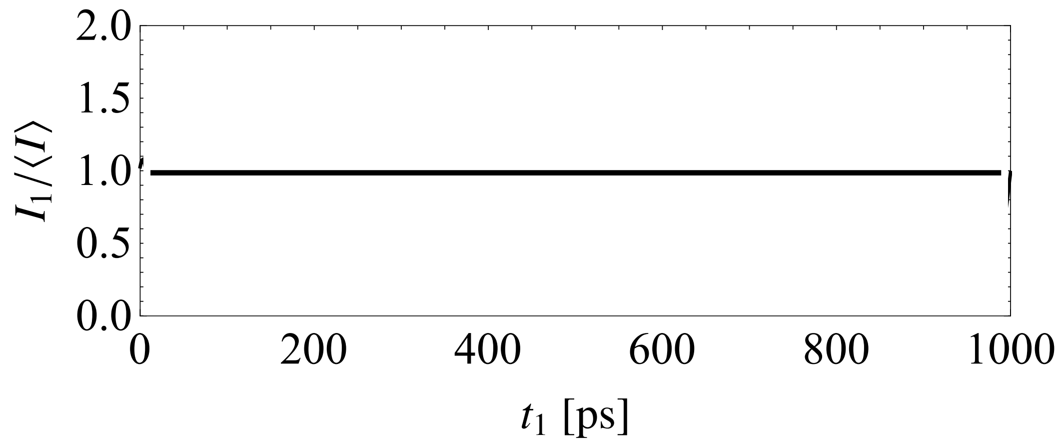
Constant intensity (laser) and/or unresolved phase fluctuations

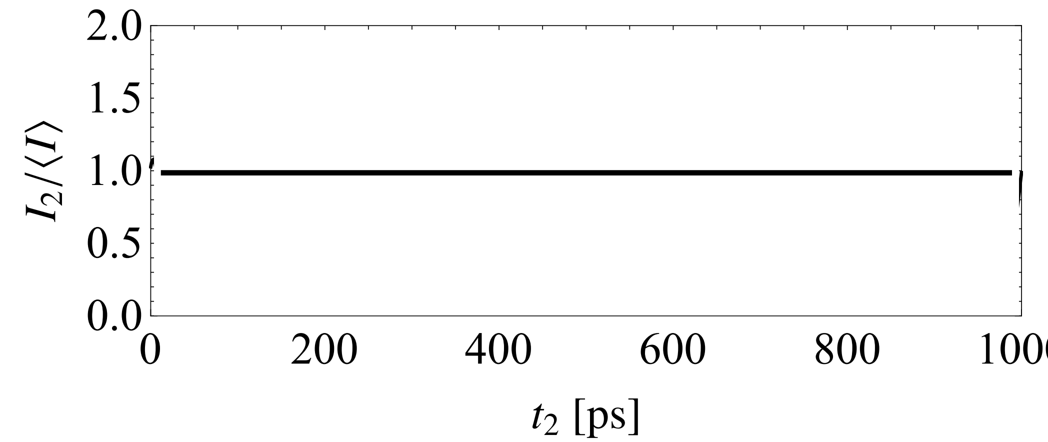


Mar´ıa J. Rioja[1,2,3] · Richard Dodson[2]

Intensity Interferometry

Second Order Correlations of Light





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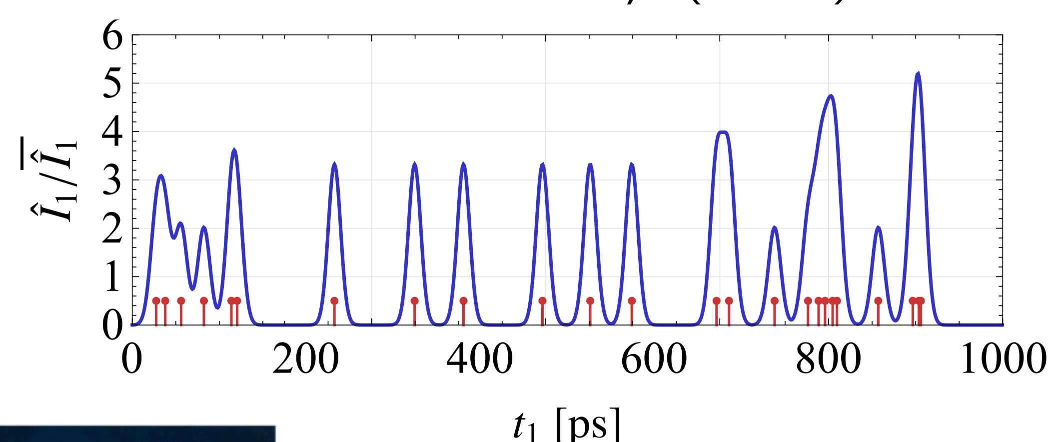
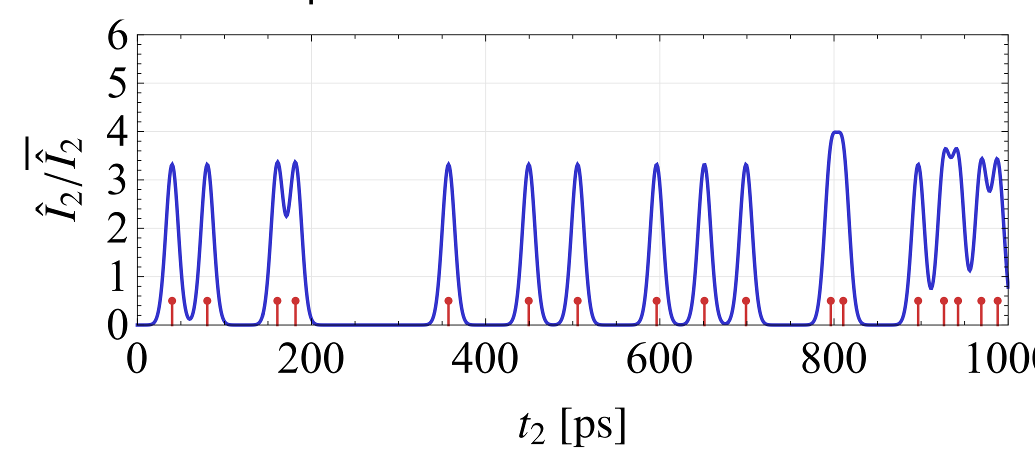
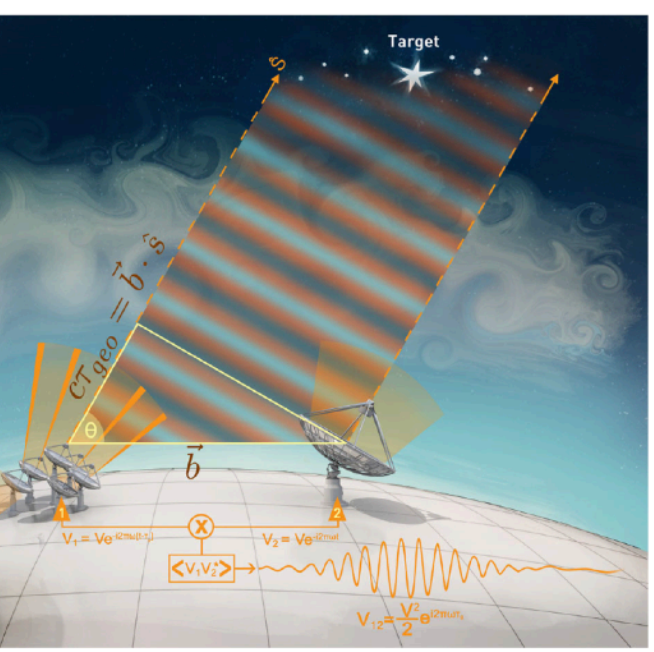




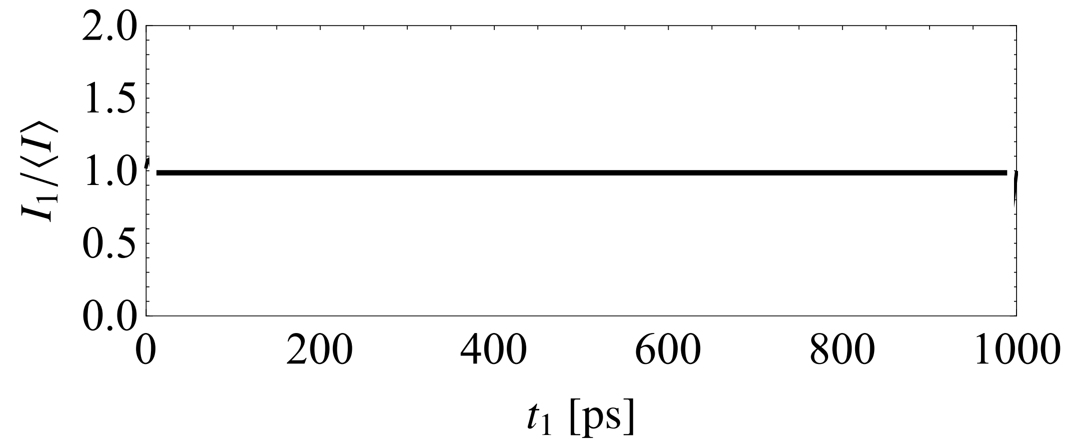


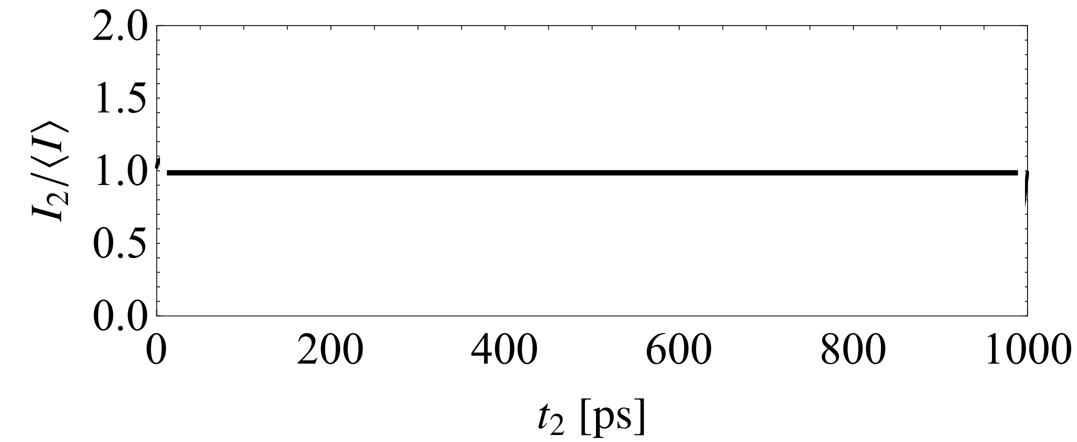
Produce random photon counts in two detectors

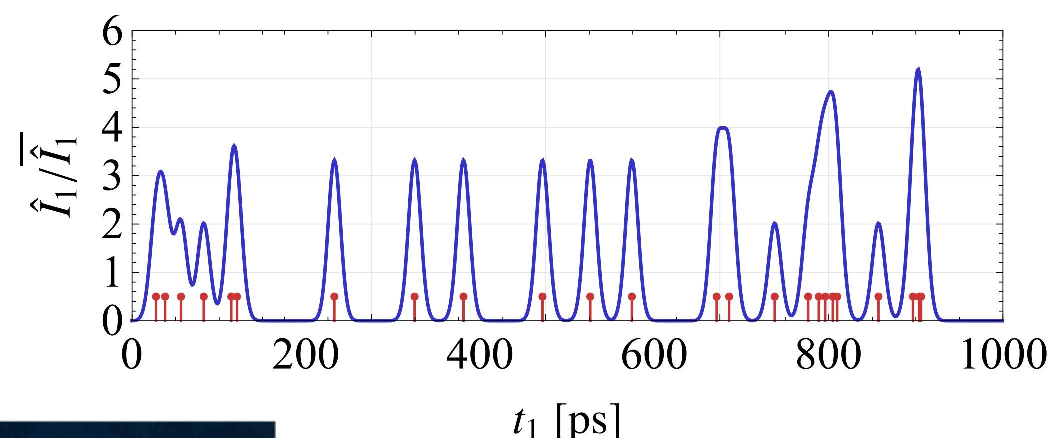
María J. Rioja[1,2,3] · Richard Dodson[2]

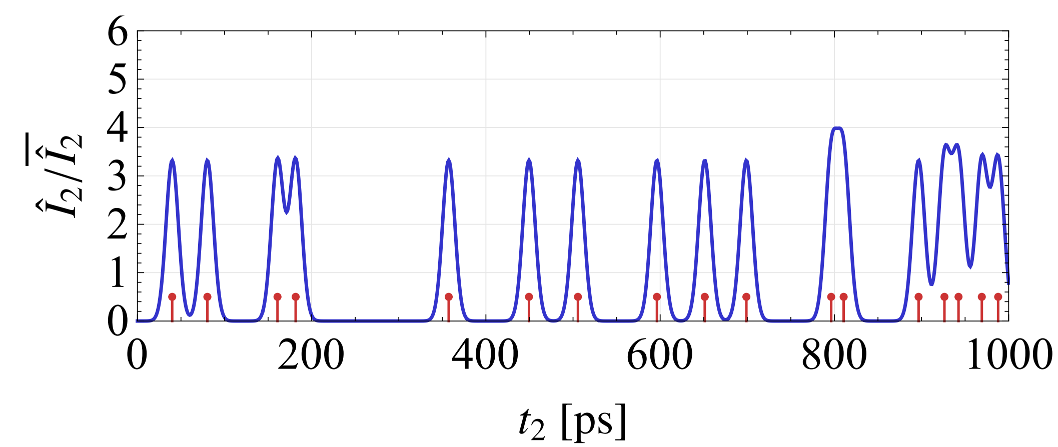
Intensity Interferometry

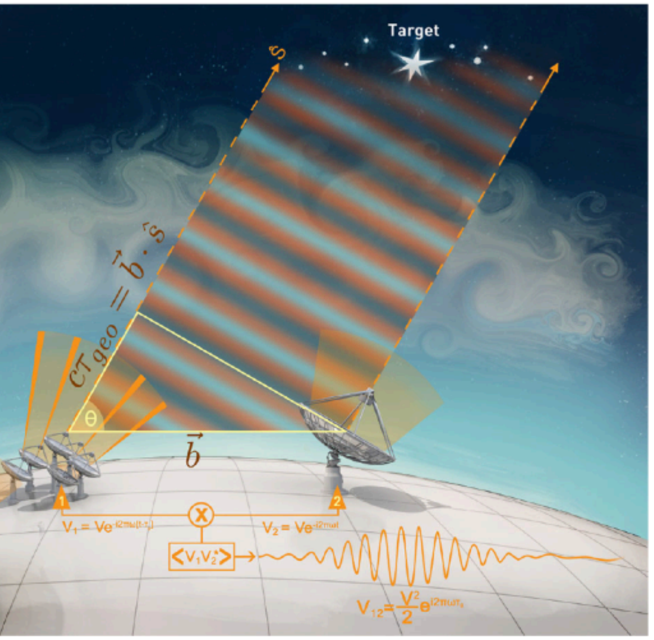
Second Order Correlations of Light





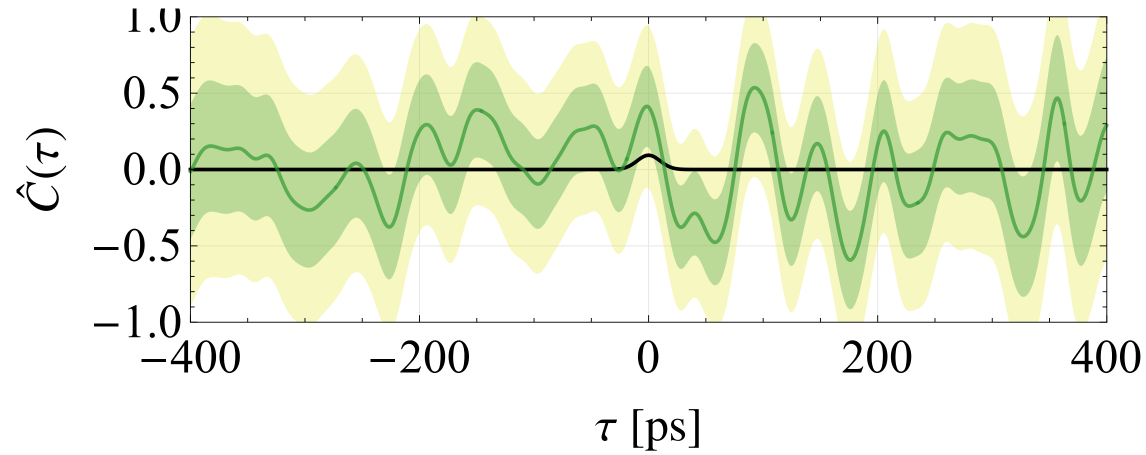






Mar´ıa J. Rioja[1,2,3] · Richard Dodson[2]

Produce random photon counts in two detectors

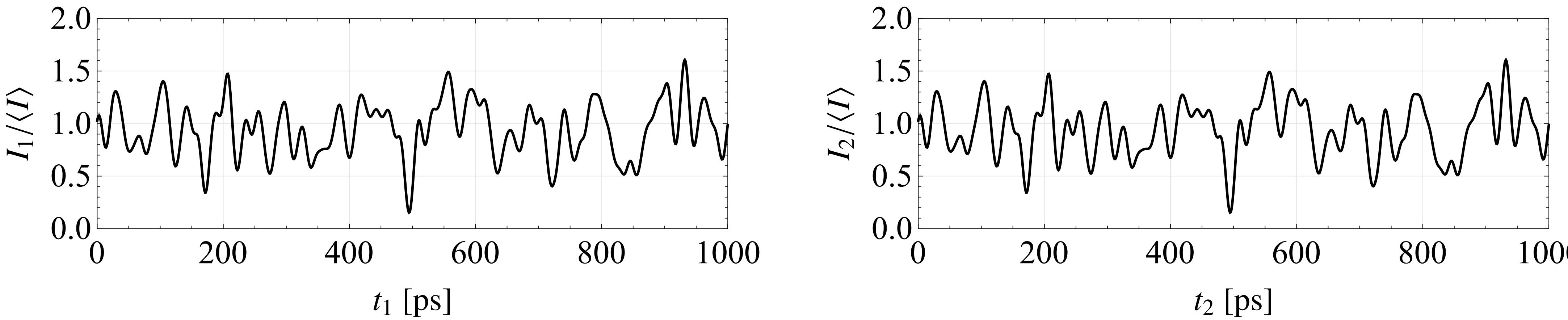


$$C(\mathbf{d}, \tau) \equiv \frac{\langle I_1(t) \langle I_2(t+\tau) \rangle \rangle}{\langle I_1 \rangle \langle I_2 \rangle} - 1$$

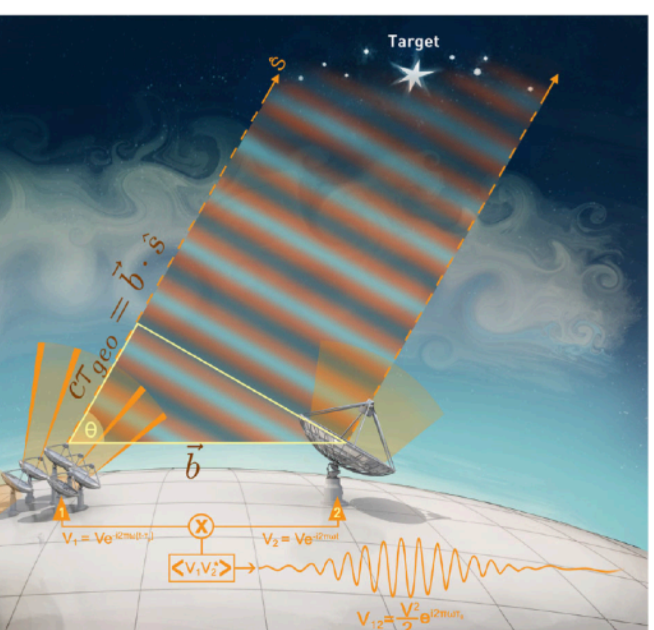
no intensity correlation

Intensity Interferometry

Second Order Correlations of Light



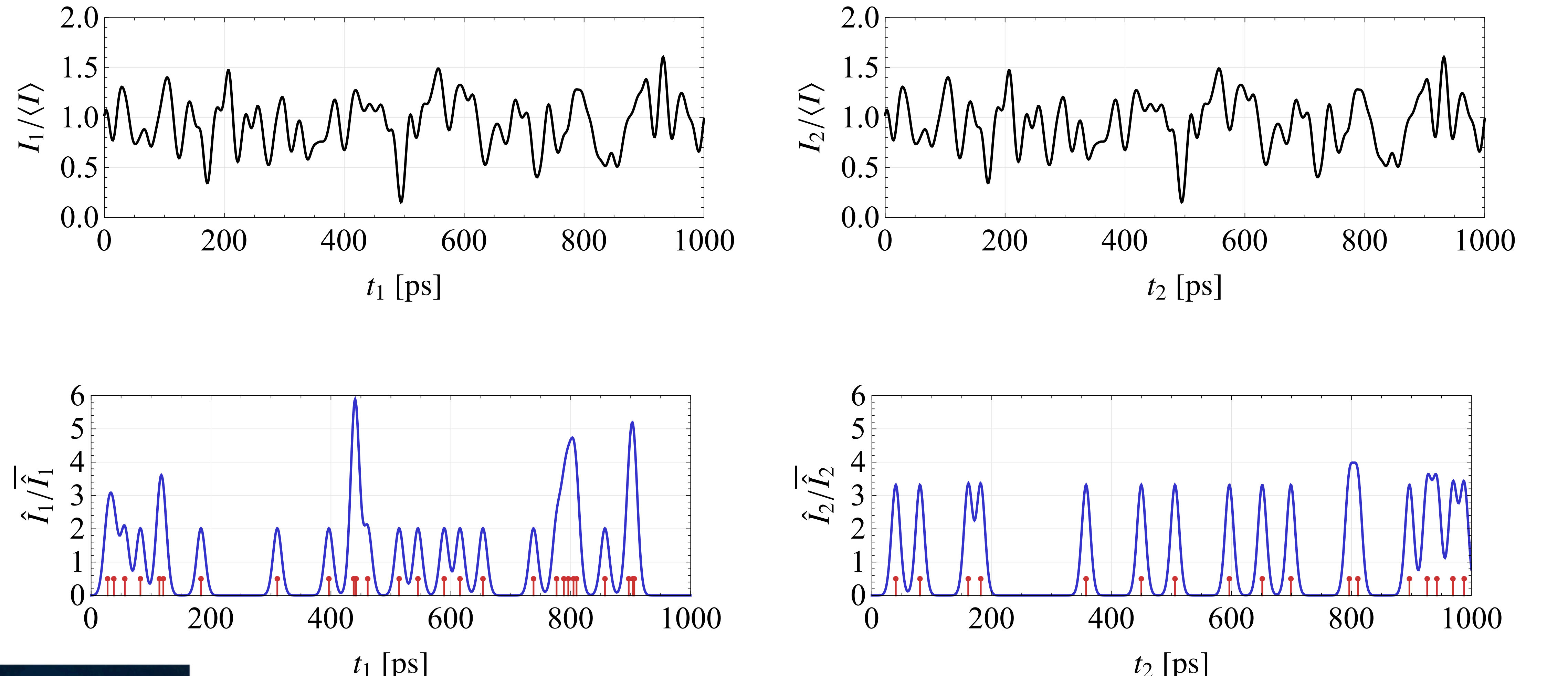
Resolving phase fluctuations (multiple frequencies/thermal source)

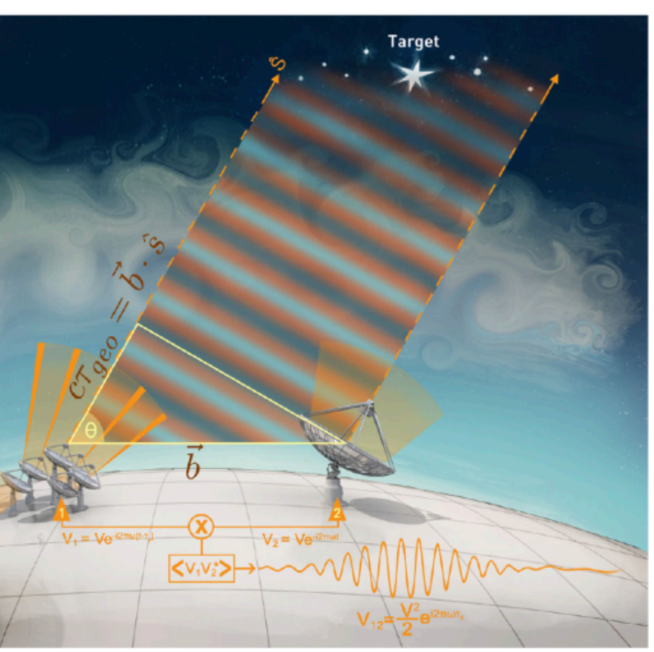


Mar´ıa J. Rioja[1,2,3] · Richard Dodson[2]

Intensity Interferometry

Second Order Correlations of Light



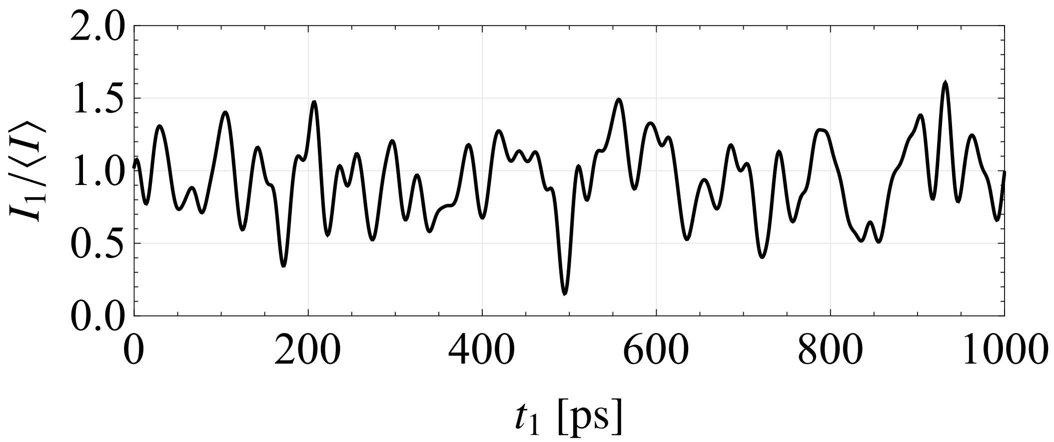


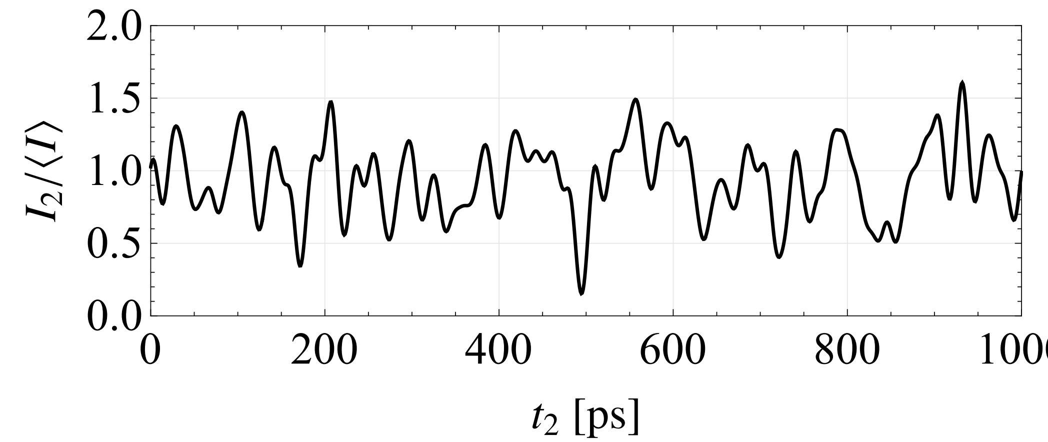
Produces interference between photon counts

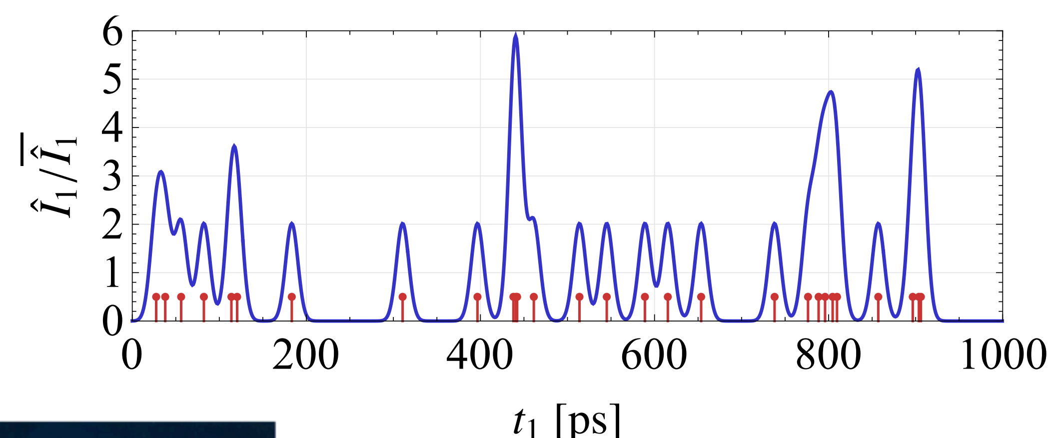
Mar´ıa J. Rioja[1,2,3] • Richard Dodson[2]

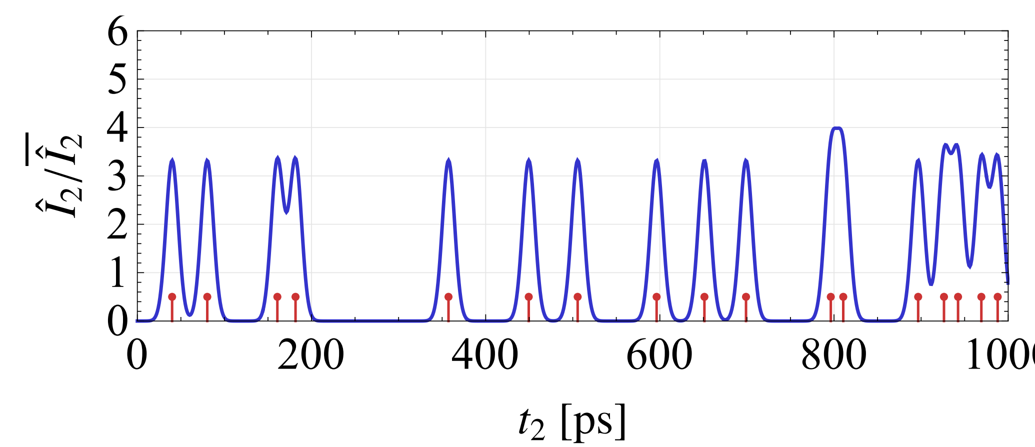
Intensity Interferometry

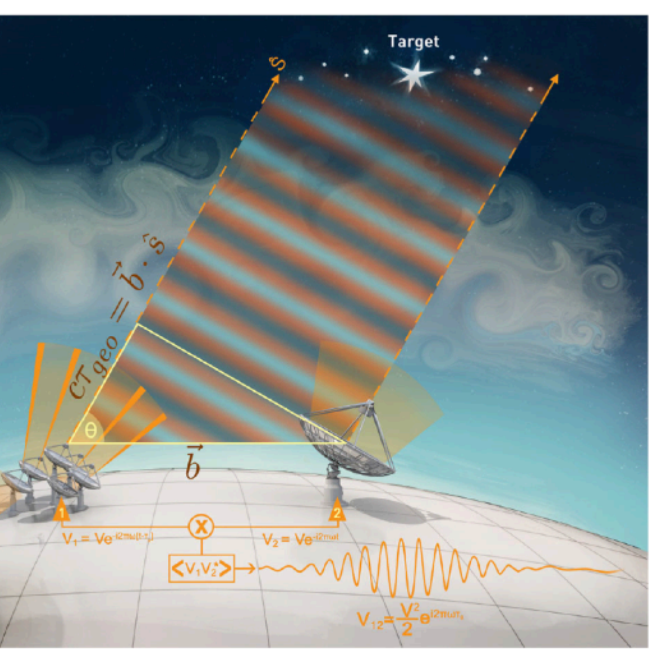
Second Order Correlations of Light

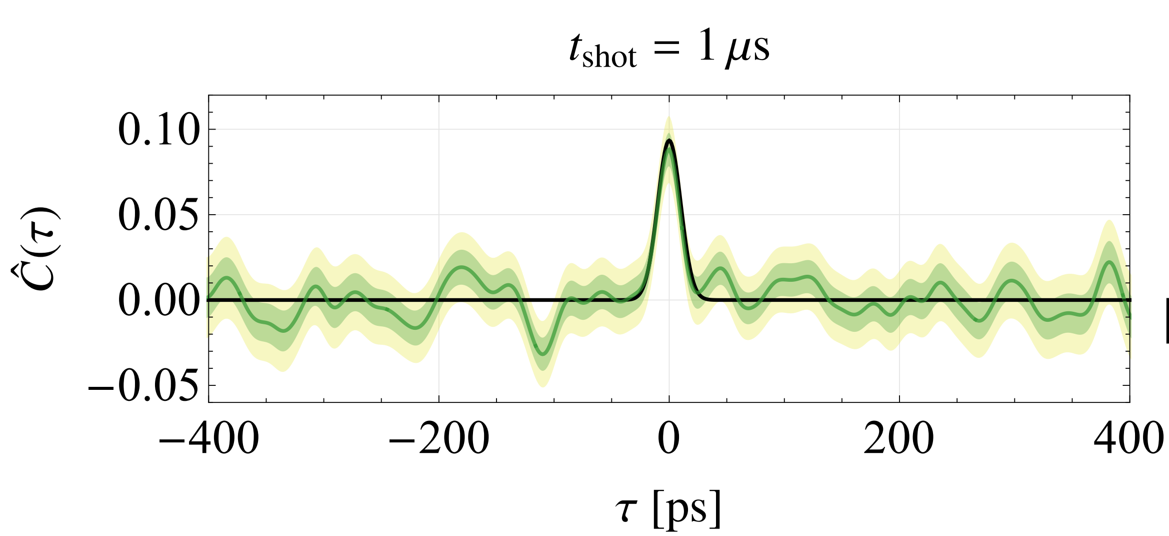












$$C(\mathbf{d},\tau) \equiv \frac{\langle I_1(t)\,\langle I_2(t+\tau)\rangle\rangle}{\langle I_1\rangle\,\langle I_2\rangle} - 1$$

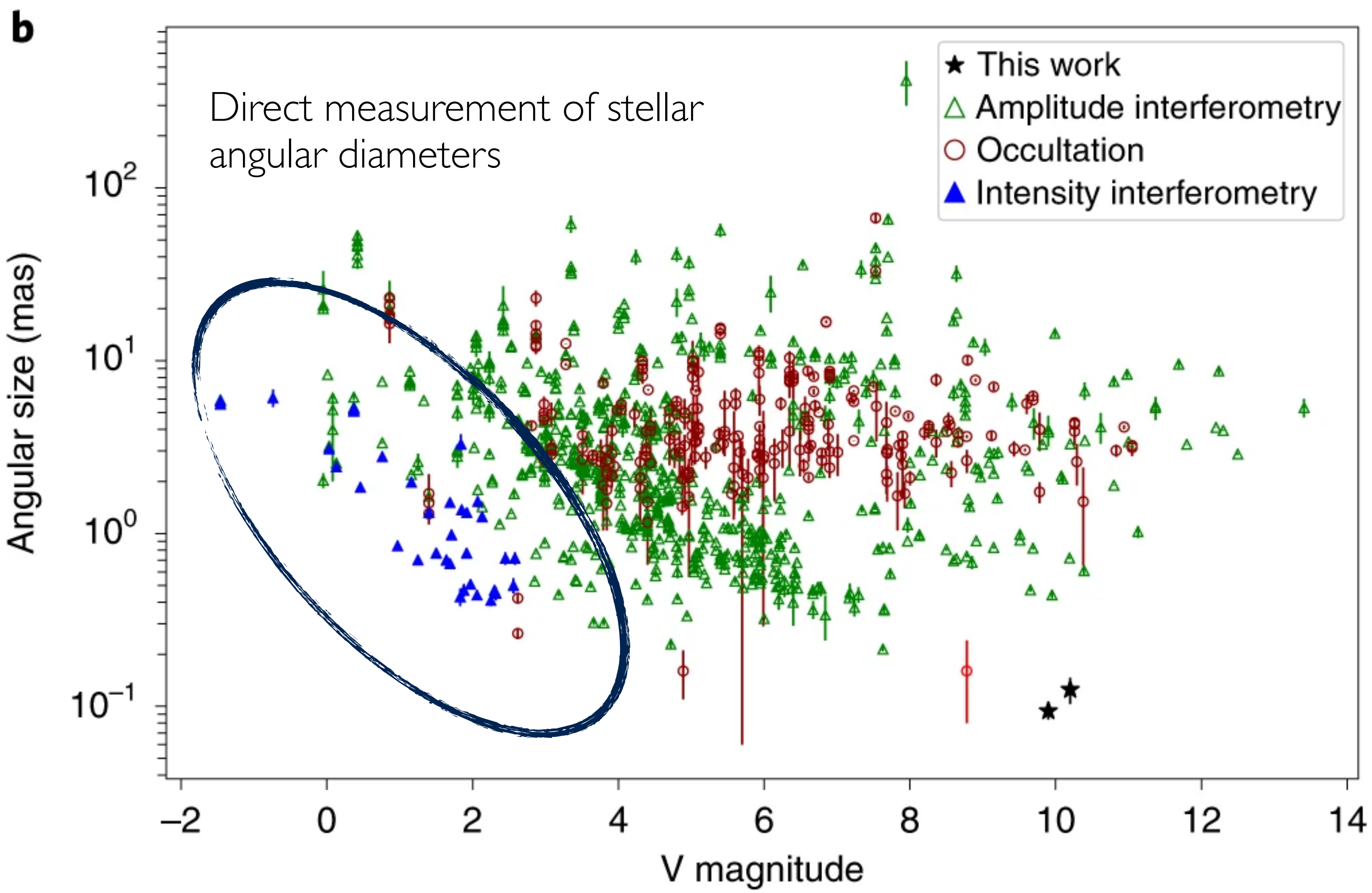
Resulting in correlations

Mar´ıa J. Rioja[1,2,3] · Richard Dodson[2]

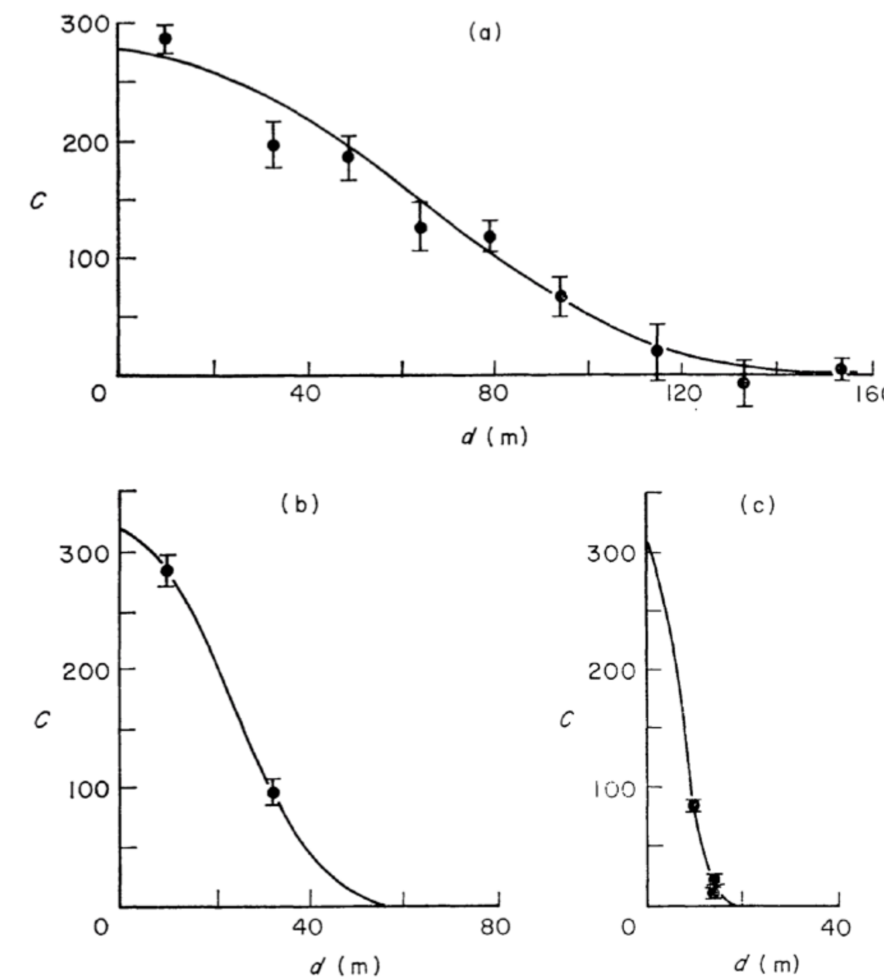
WHY NOW?

New technology

Intensity Interferometry



Benbow, W., Bird, R., Brill, A. et al. Nat Astron 3, 511–516 (2019)



$$\frac{1}{\sqrt{1+2\sigma_k^2\sigma_t^2}} \exp\left\{-\frac{\sigma_k^2}{1+2\sigma_k^2\sigma_t^2}\left(\tau+\hat{\boldsymbol{\theta}}_a\cdot\mathbf{d}\right)^2\right\}.$$

- *Best sensitivity for bright stars*
- *Need high statistics of coincident photons, not total photons*

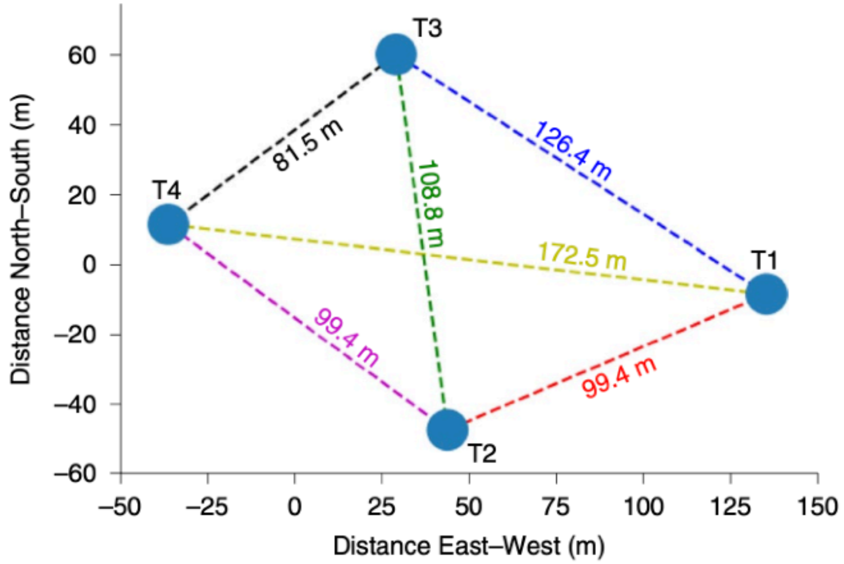
$$\mathrm{SNR} \sim \epsilon_T \sqrt{N_{\mathrm{coincident}}}$$

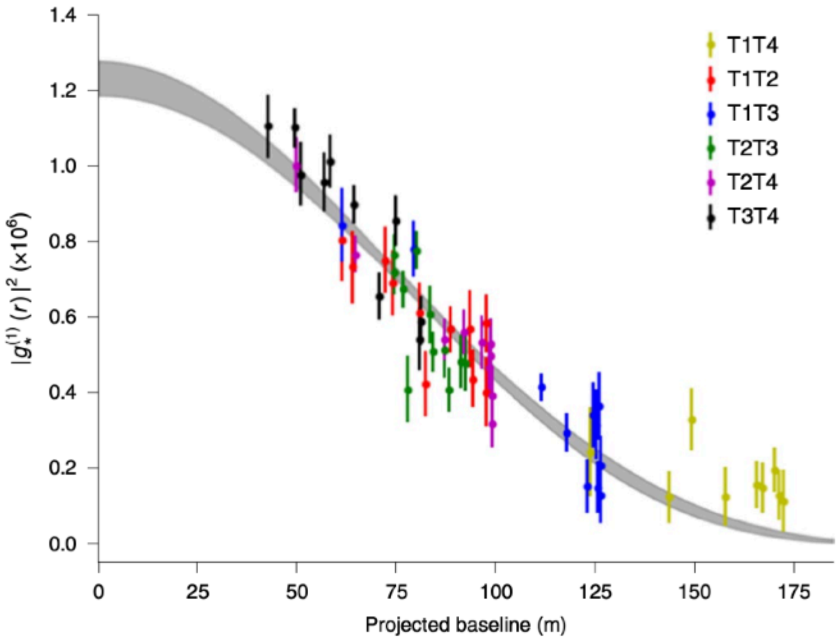
$$\sim \tau_{\mathrm{coh}} \sqrt{\frac{t_{\mathrm{obs}}}{\sigma_t}} D^2 \times \mathrm{flux}$$

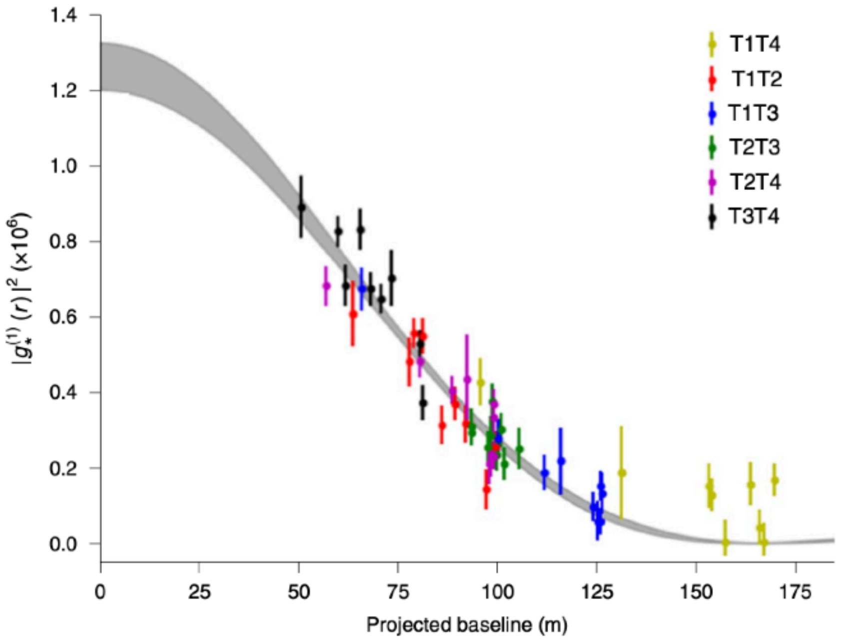
Intensity Interferometry

- ***Large dishes*** allow for fainter sources

"more precise angular diameter measurements than the NSII, in less than one tenth of the observation time"







LETTERS
https://doi.org/10.1038/s41550-020-1143-y
nature astronomy
Check for updates

Demonstration of stellar intensity interferometry with the four VERITAS telescopes

A. U. Abeysekara[1], W. Benbow[2], A. Brill[3], J. H. Buckley[4], J. L. Christiansen[5], A. J. Chromey[6], M. K. Daniel[2], J. Davis[1], A. Falcone[7], Q. Feng[8], J. P. Finley[9], L. Fortson[10], A. Furniss[11], A. Gent[12], C. Giuri[13], O. Gueta[13], D. Hanna[14], T. Hassan[13], O. Hervet[15], J. Holder[16], G. Hughes[2], T. B. Humensky[3], P. Kaaret[17], M. Kertzman[18], D. Kieda[1]✉, F. Krennrich[6], S. Kumar[14], T. LeBohec[1], T. T. Y. Lin[14], M. Lundy[14], G. Maier[13], N. Matthews[1]✉, P. Moriarty[19], R. Mukherjee[8], M. Nievas-Rosillo[13], S. O'Brien[14], R. A. Ong[20], A. N. Otte[12], K. Pfrang[13], M. Pohl[13,21], R. R. Prado[13], E. Pueschel[13], J. Quinn[22], K. Ragan[14], P. T. Reynolds[23], D. Ribeiro[3], G. T. Richards[16], E. Roache[2], J. L. Ryan[20], M. Santander[24], G. H. Sembroski[9], S. P. Wakely[25], A. Weinstein[6], P. Wilcox[10], D. A. Williams[15] and T. J. Williamson[16]

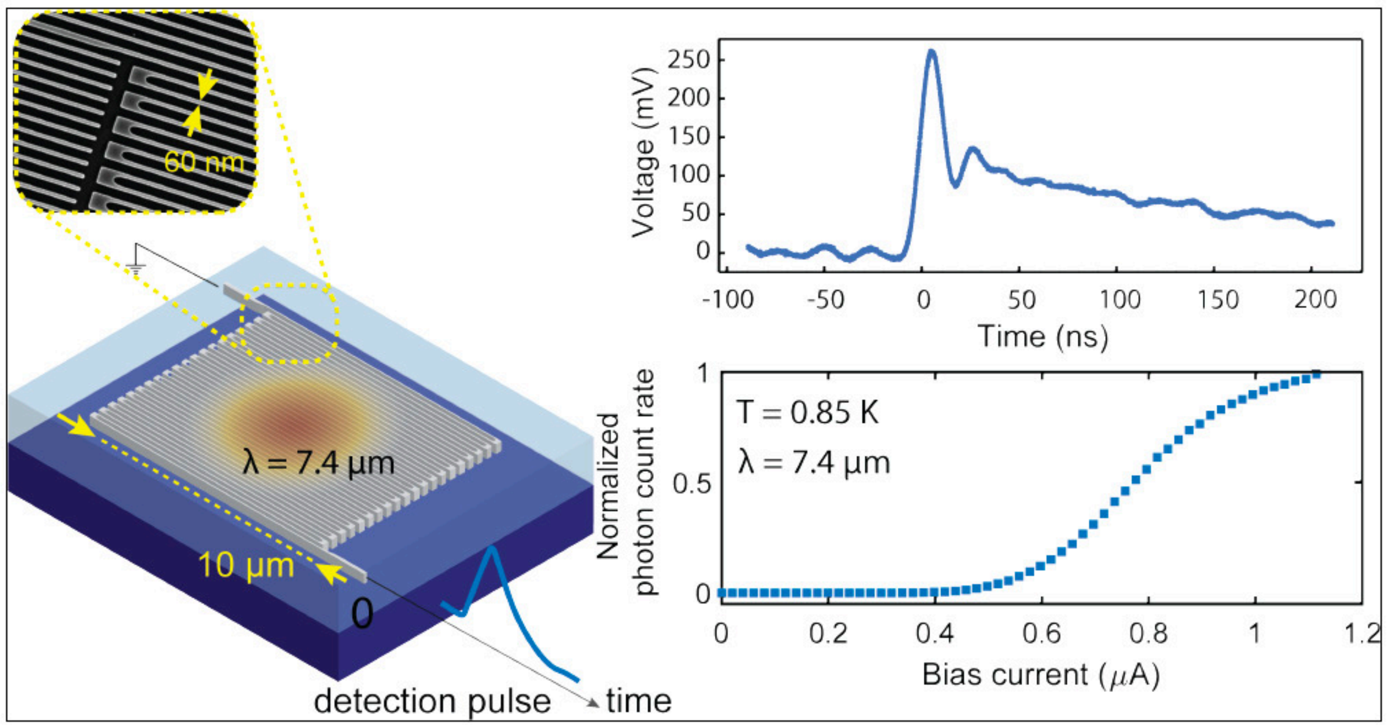
Intensity Interferometry

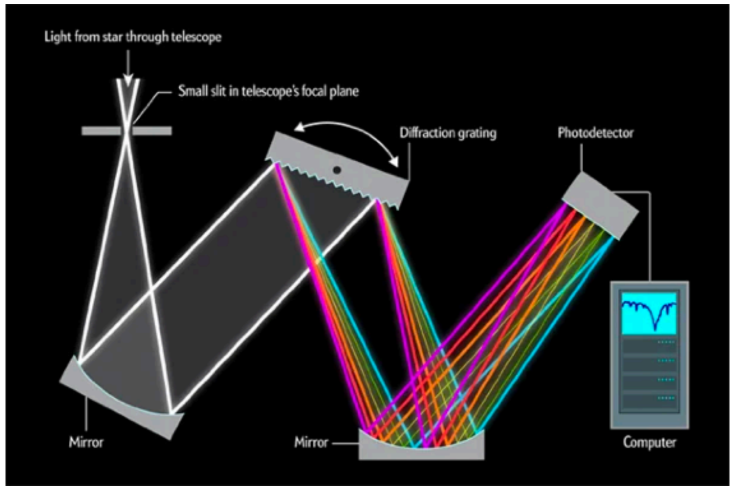
- ***Fast, efficient detectors*** allow for fainter sources

$$C(\mathbf{d},\tau) = \frac{1}{\sqrt{1+2\sigma_k^2\sigma_t^2}} \exp\left\{-\frac{\sigma_k^2}{1+2\sigma_k^2\sigma_t^2}\left(\tau+\hat{\boldsymbol{\theta}}_a\cdot\mathbf{d}\right)^2\right\}.$$

$$\mathrm{SNR} \sim \epsilon_T \sqrt{N_{\mathrm{coincident}}}$$

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





Fast Single-Photon Detection

Multi-Channel Spectroscopy

e.g.

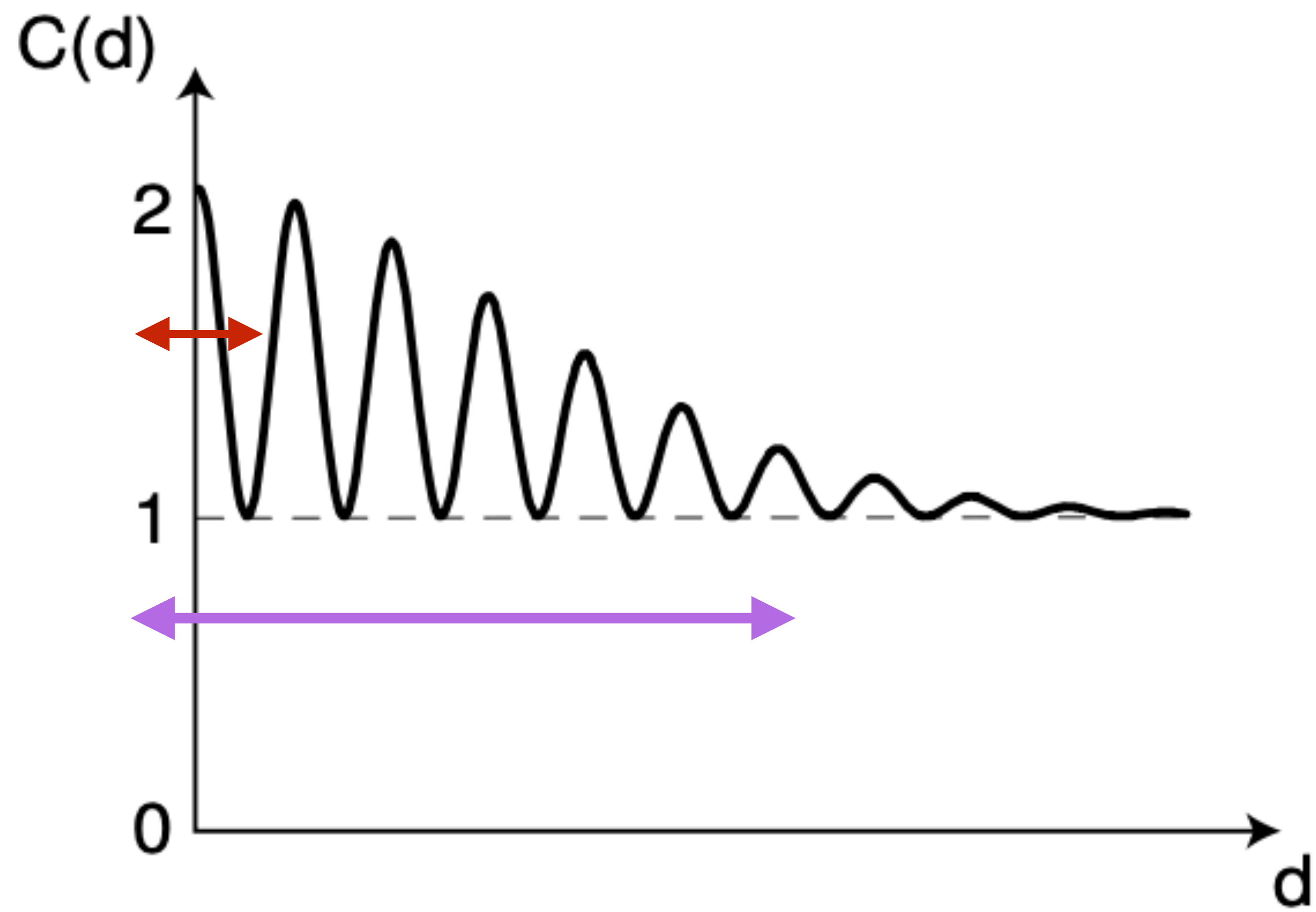
Boris Korzh, Qing-Yuan Zhao, Jason P Allmaras, Simone Frasca, Travis M Autry, Eric A Bersin, Andrew D Beyer, Ryan M Briggs, Bruce Bumble, Marco Colangelo, et al. Demonstration of sub-3 ps temporal resolution with a superconducting nanowire single-photon detector. *Nature Photonics*, 14(4):250–255, 2020. — 3ps

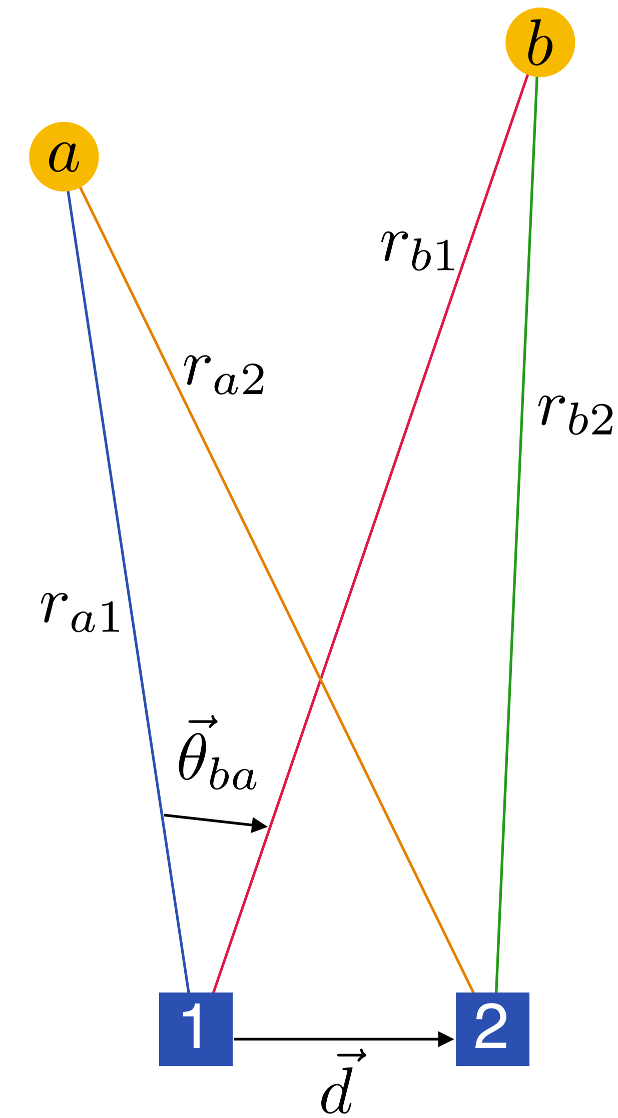
Mirko Sanzaro, Paolo Gattari, Federica Villa, Alberto Tosi, Giuseppe Croce, and Franco Zappa. Single-photon avalanche diodes in a 0.16 μm bcd technology with sharp timing response and red-enhanced sensitivity. *IEEE Journal of Selected Topics in Quantum Electronics*, 24(2):1–9, 2018. — 28 ps

WHY NOW?

Extended path idea expands field of view and applications

Intensity Interferometry: Field of View

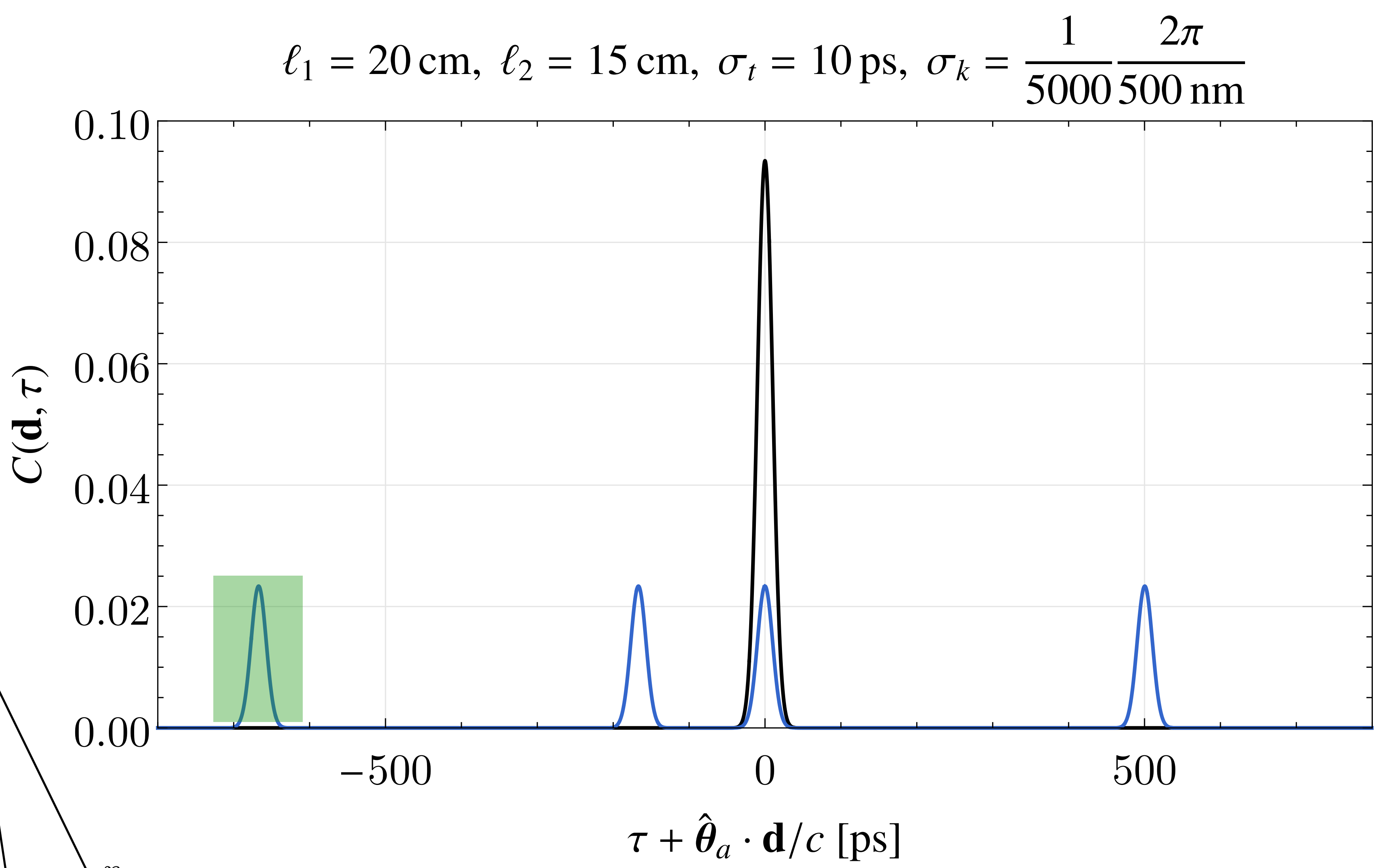


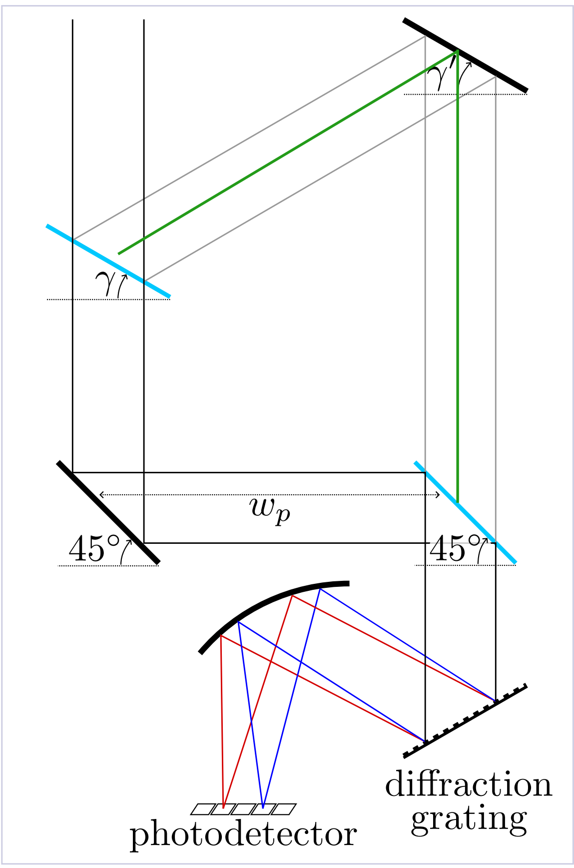


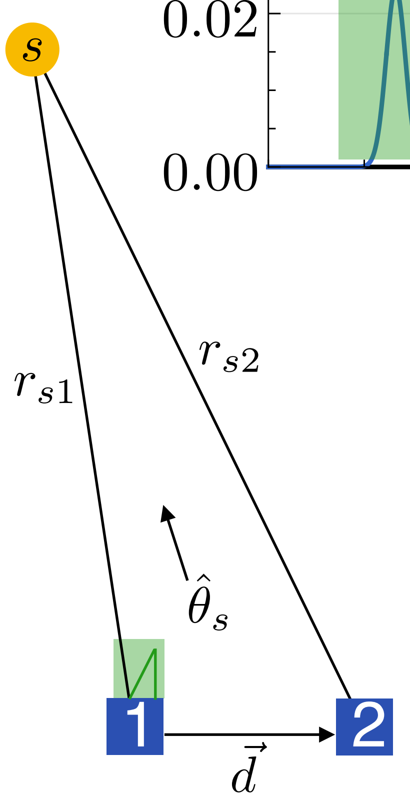
$$C^{\text{opt}}(\mathbf{d}) = \frac{1}{\sqrt{2}\sigma_k\sigma_t}\left\{(\widetilde{I}_a^2 + \widetilde{I}_b^2)\, e^{\frac{-(\boldsymbol{\theta}_{ba}\cdot\mathbf{d})^2}{8\sigma_t^2}} + 2\widetilde{I}_a\widetilde{I}_b \cos\left[\bar{k}\mathbf{d}\cdot\boldsymbol{\theta}_{ba}\right] e^{\frac{-\sigma_k^2(\boldsymbol{\theta}_{ba}\cdot\mathbf{d})^2}{4}}\right\}$$

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

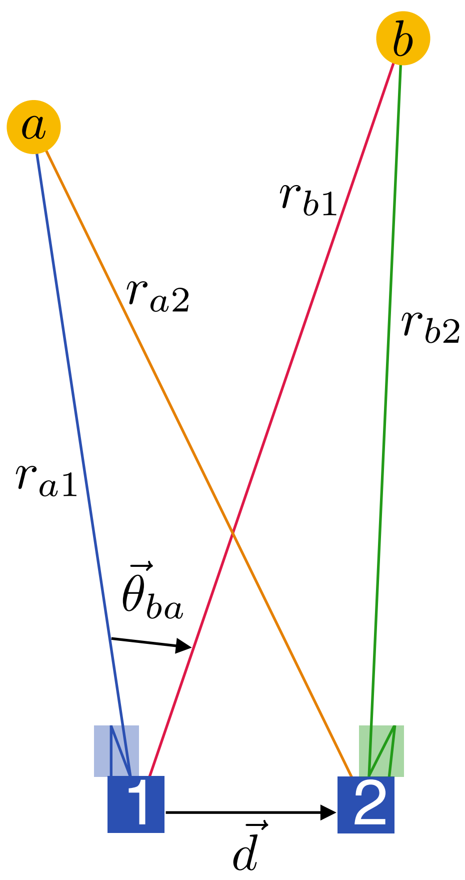
Intensity Interferometry: Extended Path

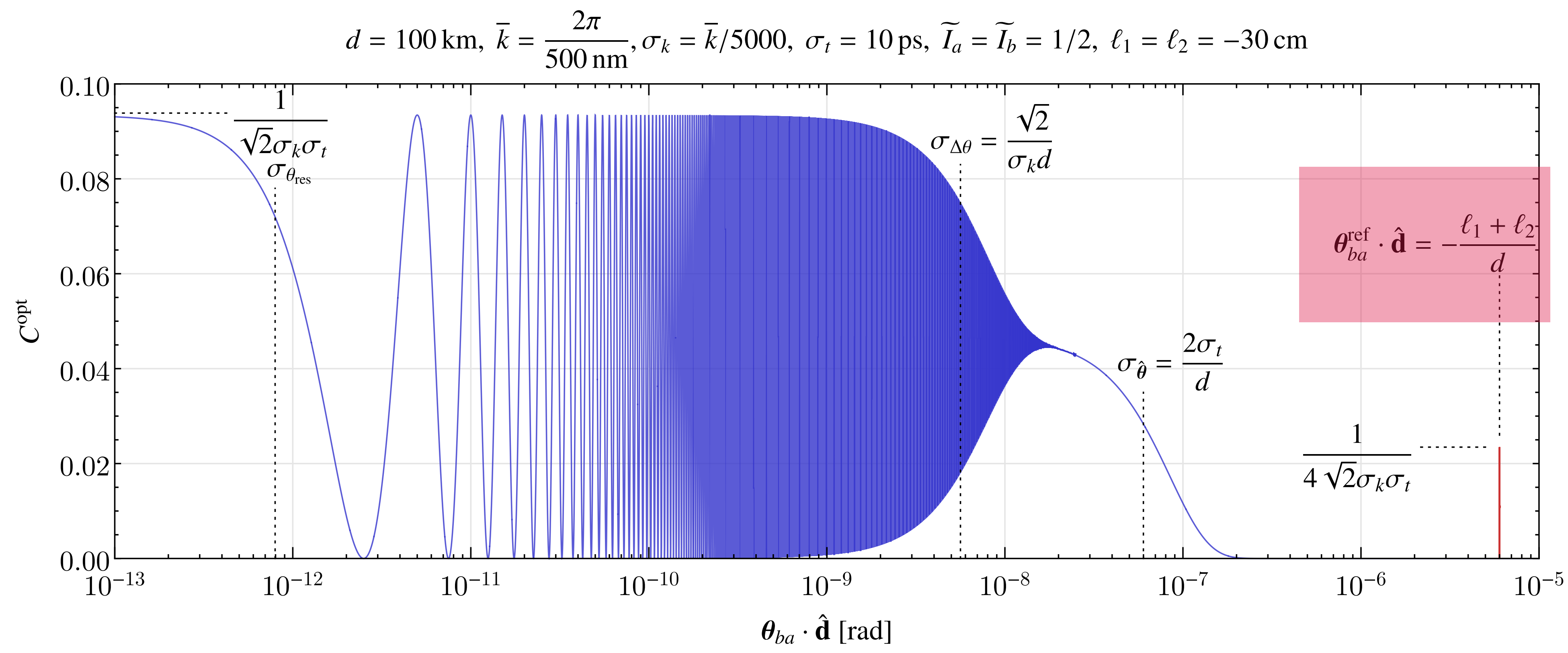






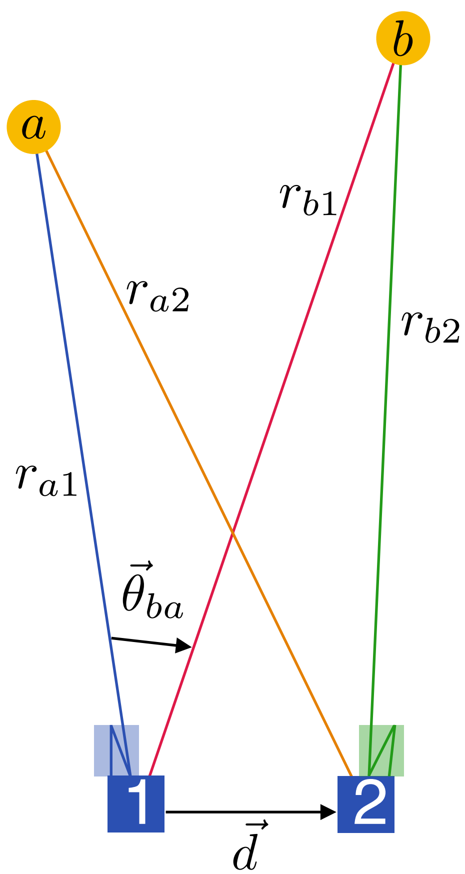
Intensity Interferometry: Field of View

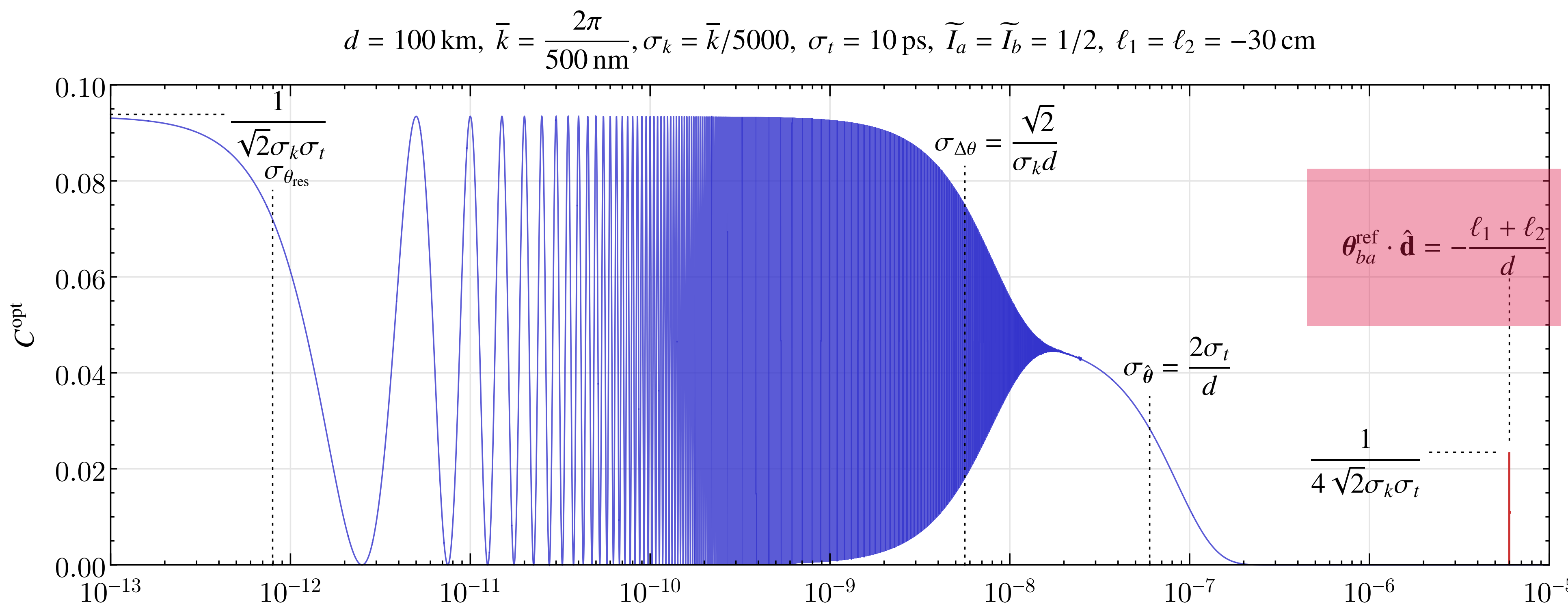


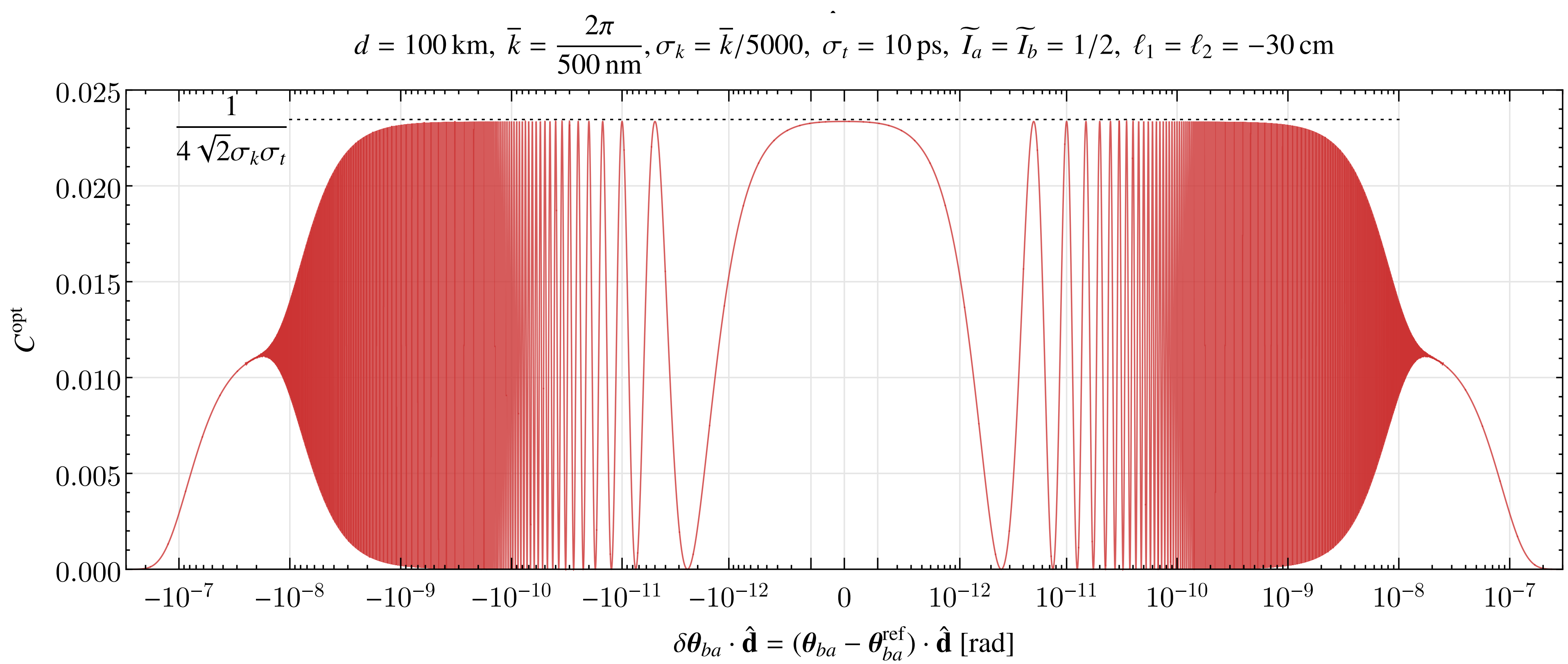


$$\sigma_{\theta_{\text{res}}} \sim \frac{\lambda}{d} \sim \underbrace{10^{-12}\,\text{rad}}_{0.2\,\mu\text{as}} \left(\frac{\lambda}{500\,\text{nm}}\right)\left(\frac{100\,\text{km}}{d}\right)$$

Intensity Interferometry: Field of View

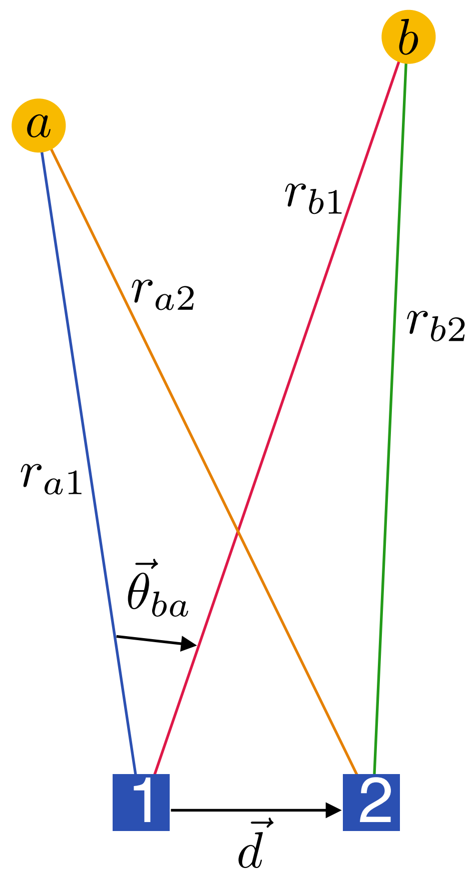


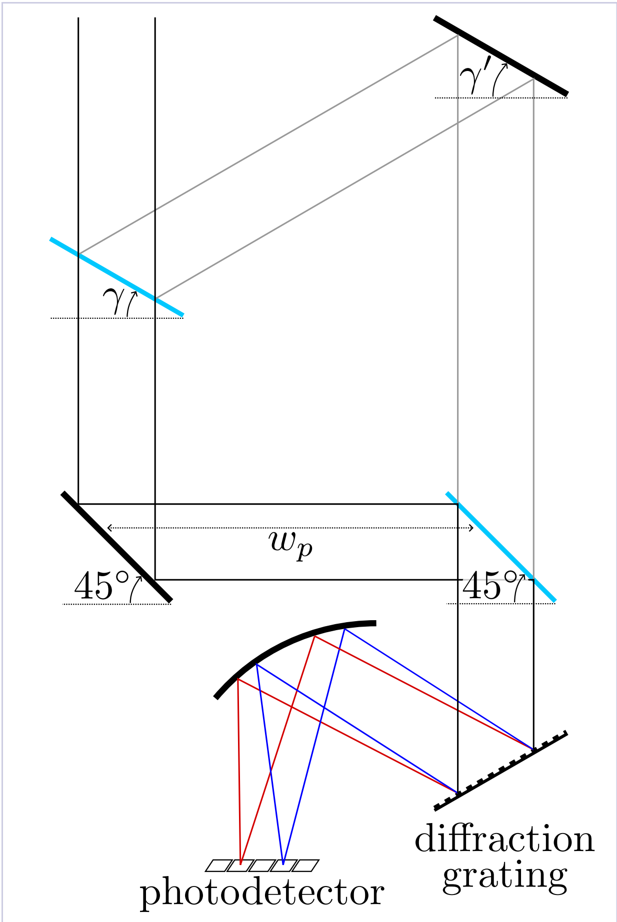




$$\sigma_{\theta_{\mathrm{res}}} \sim \frac{\lambda}{d} \sim \underbrace{10^{-12}\,\mathrm{rad}}_{0.2\,\mu\mathrm{as}} \left(\frac{\lambda}{500\,\mathrm{nm}}\right)\left(\frac{100\,\mathrm{km}}{d}\right)$$

Intensity Interferometry

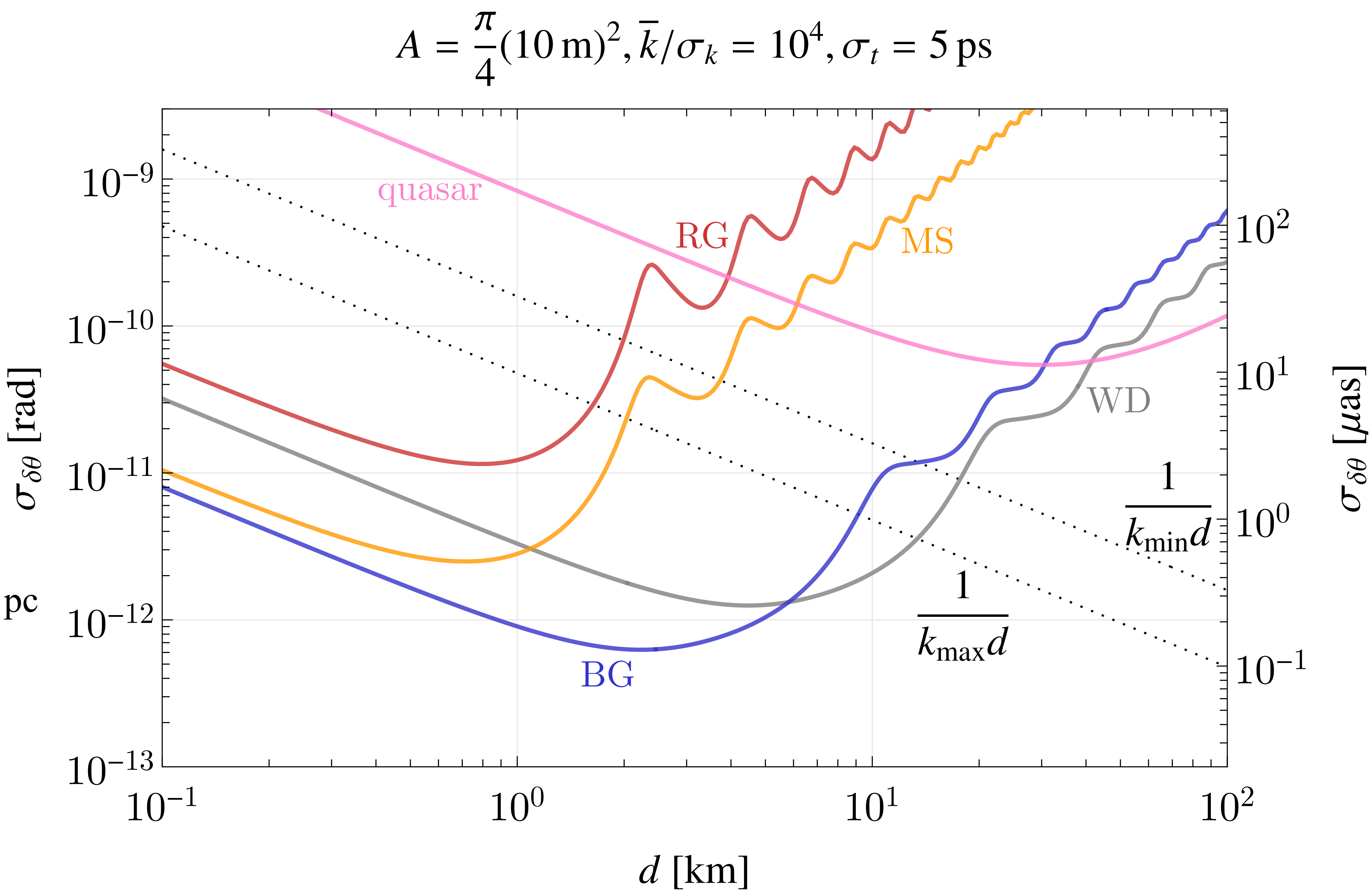




Measure separation of bright, closely separated*
sources to unprecedented precision

*O(as), due to atmospheric fluctuations

Light Centroiding Precision



WD @ 10 pc

Sun-like MS @ 100 pc

RG/BG @ 5 kpc

bright quasar

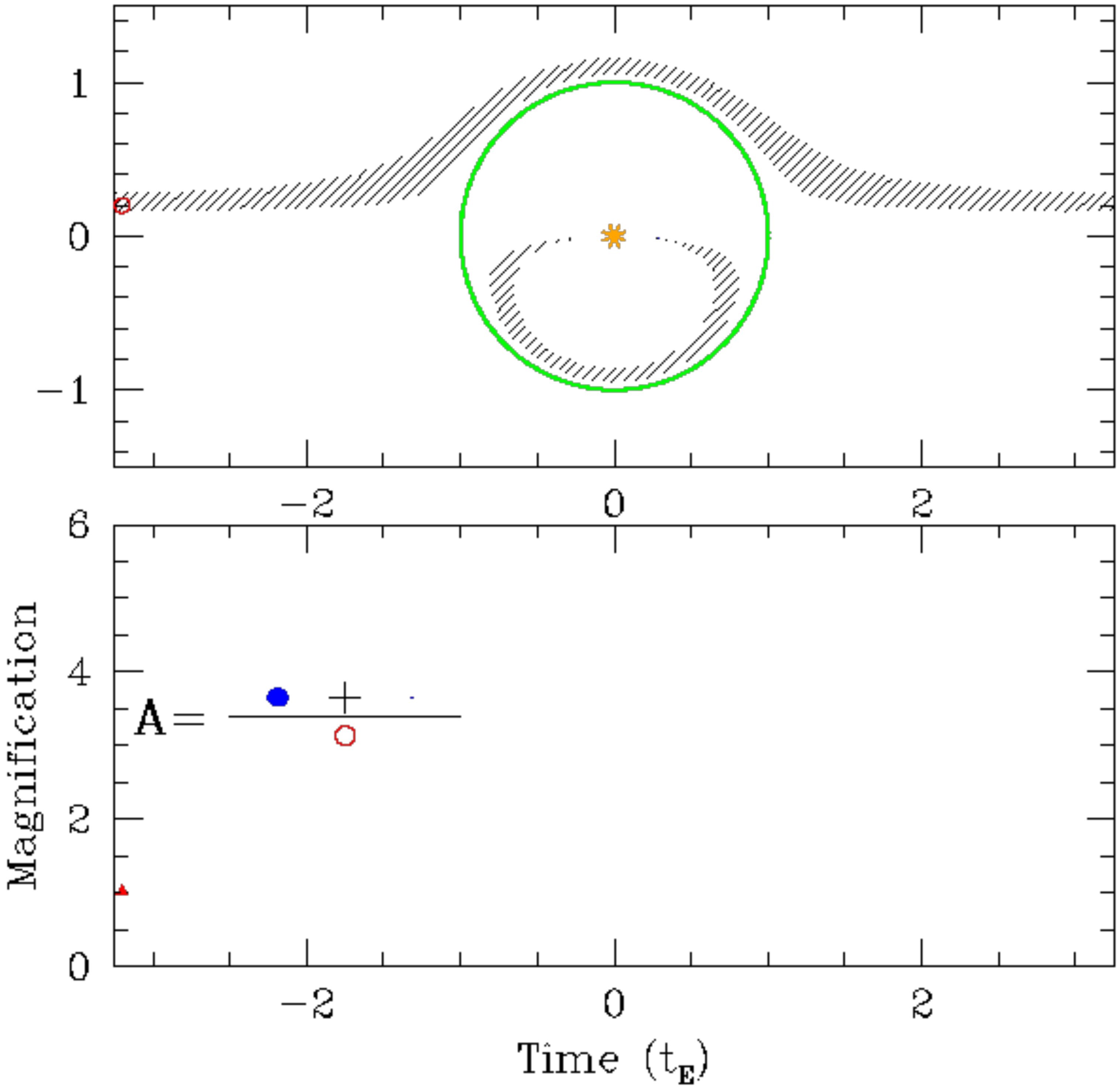
$$\sigma_{\theta_{\rm res}} \sim \frac{\lambda}{d} \sim \underbrace{10^{-12}\,\mathrm{rad}}_{0.2\,\mu\mathrm{as}} \left(\frac{\lambda}{500\,\mathrm{nm}}\right)\left(\frac{100\,\mathrm{km}}{d}\right)$$

$$\sigma_{\delta\theta} \sim \frac{1}{\sqrt{N_1 N_2}} \frac{1}{Ad} \sqrt{\frac{\sigma_t}{t_{\rm shot}}} \sqrt{\frac{\sigma_k}{k}} \frac{1}{T_s^3 \theta_s^2}$$

Outline

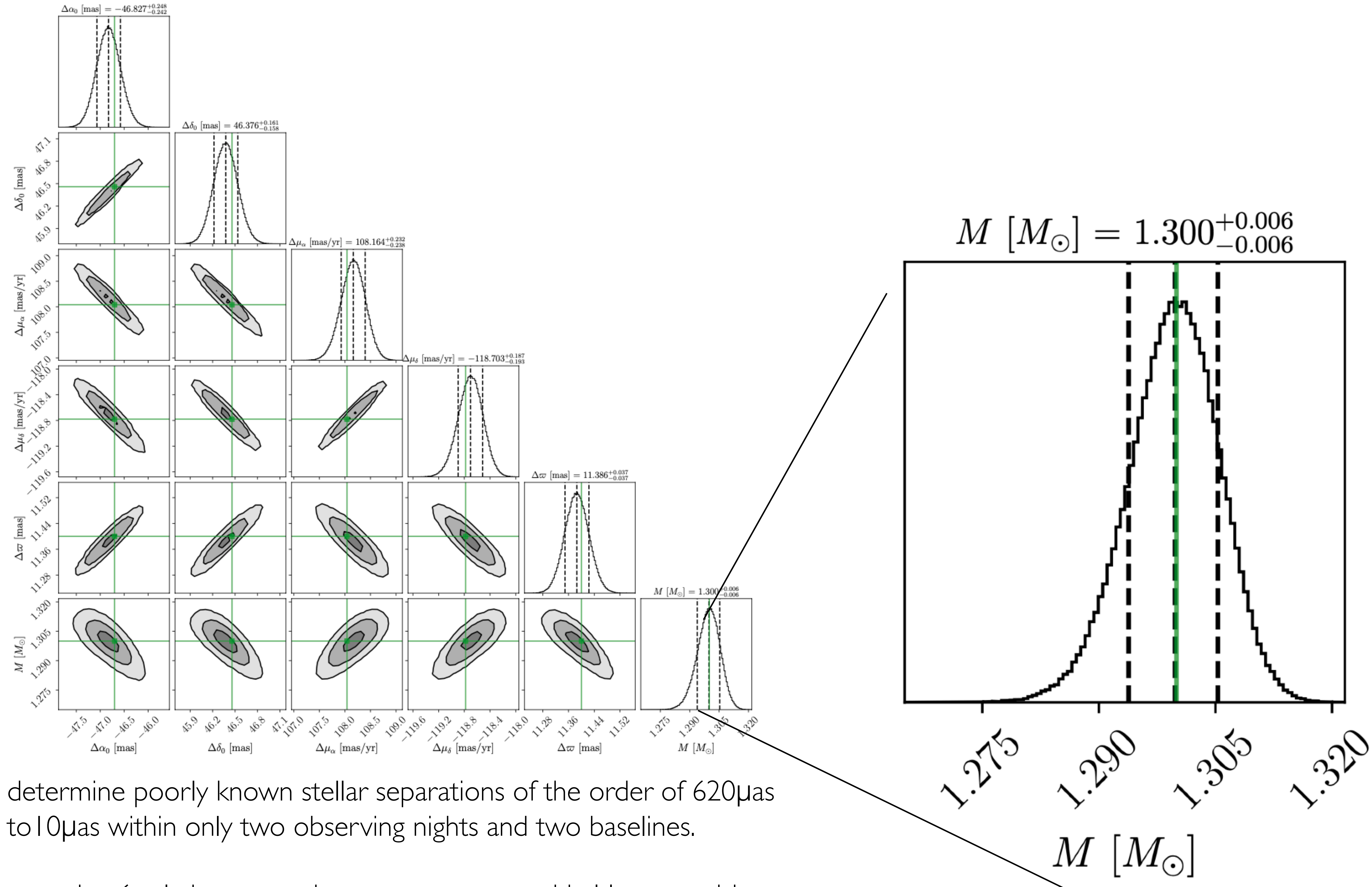
- Precision Astrometry
- Intensity interferometry
- Science cases

Applications: Stellar Microlensing



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

Applications: Stellar Microlensing

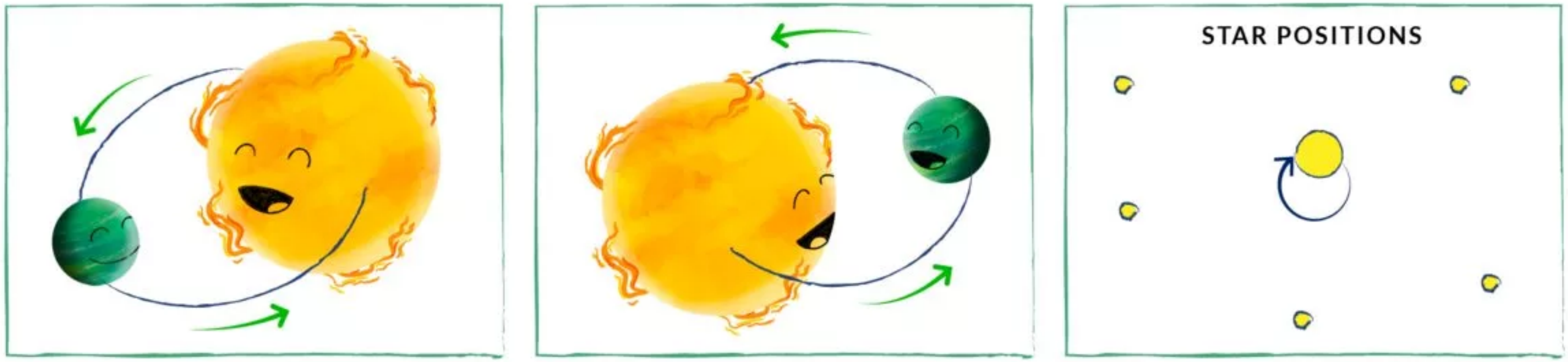


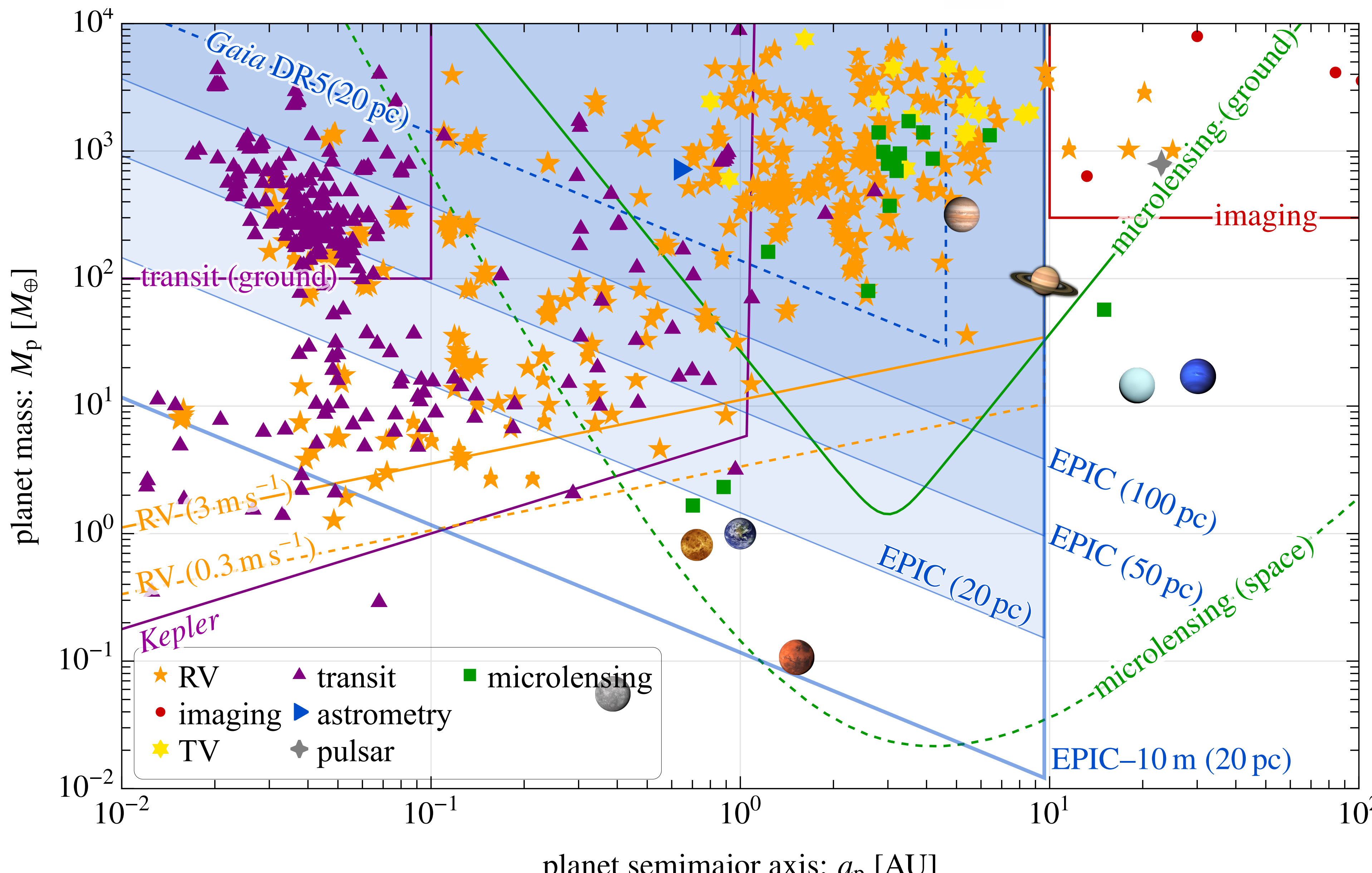
- determine poorly known stellar separations of the order of 620μas to10μas within only two observing nights and two baselines.

- assuming 6 relative separation measurements with 11μas precision over a year around the closest approach of the two stars, determine mass to sub percent precision

(compare to 15% for Gaia projections)

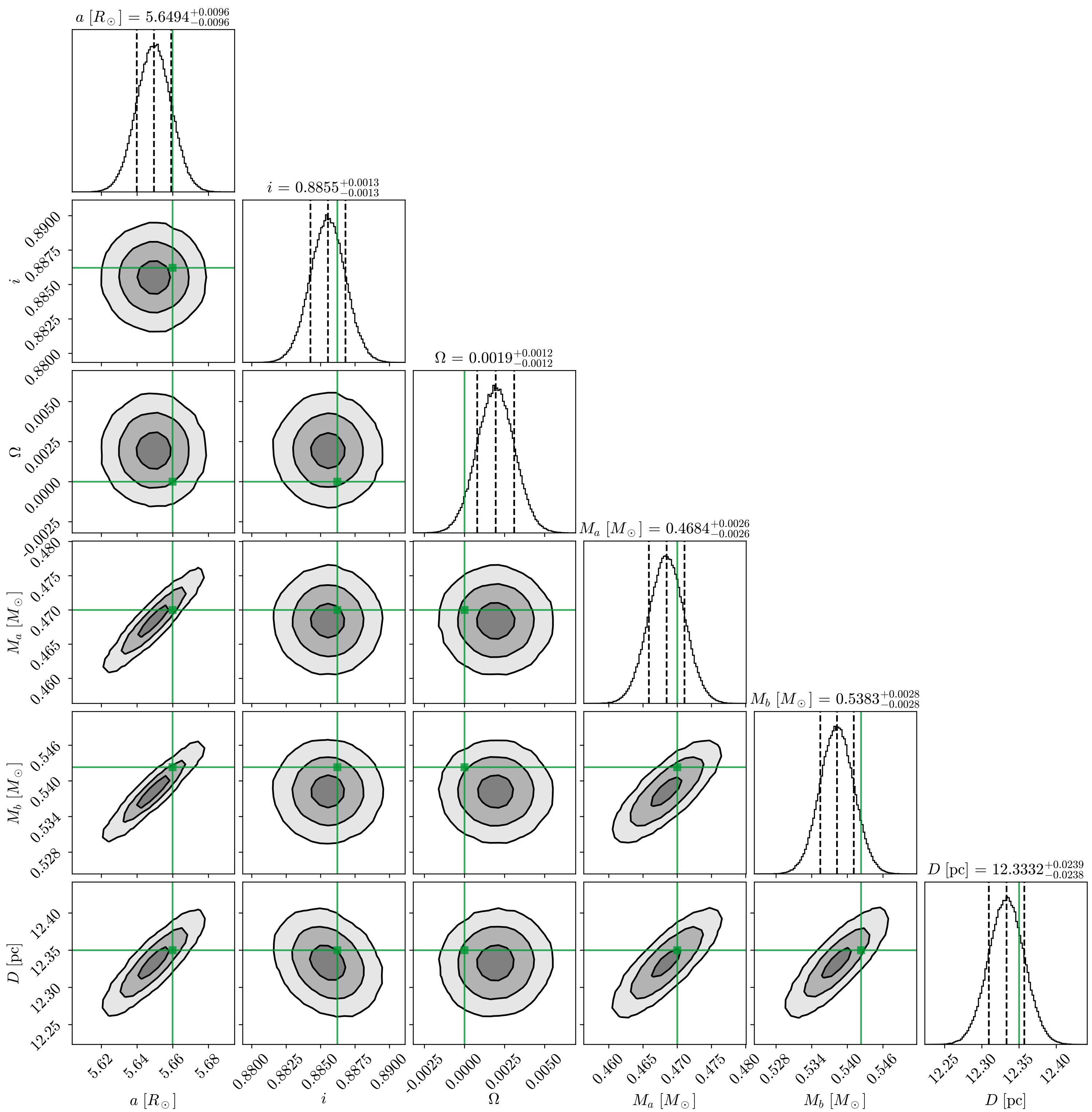
Applications: Exoplanets

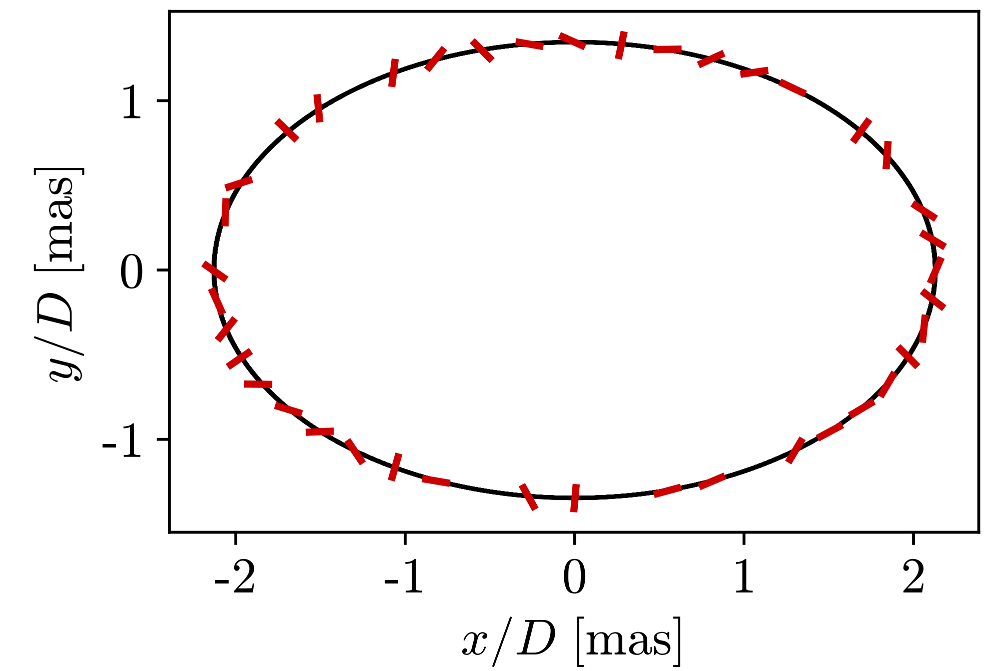


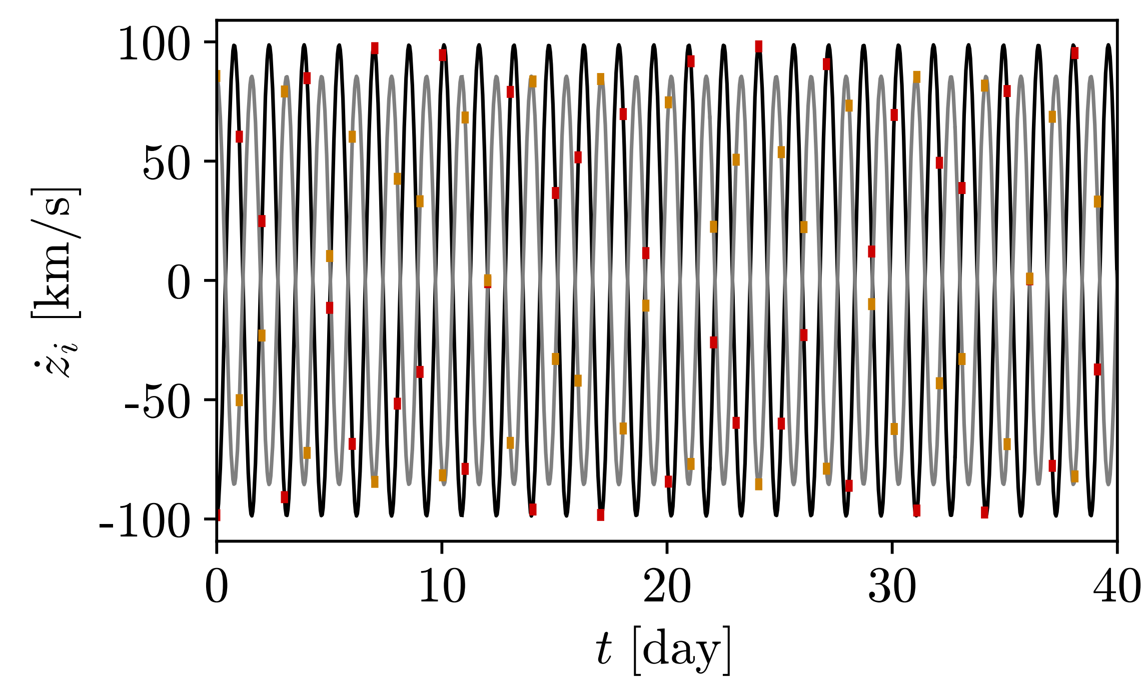


$$\Delta\theta_{\rm star} \sim \frac{M_{\rm p}}{M_{\rm star}} \frac{a_{\rm p}}{D}$$

Applications: Binary Orbits

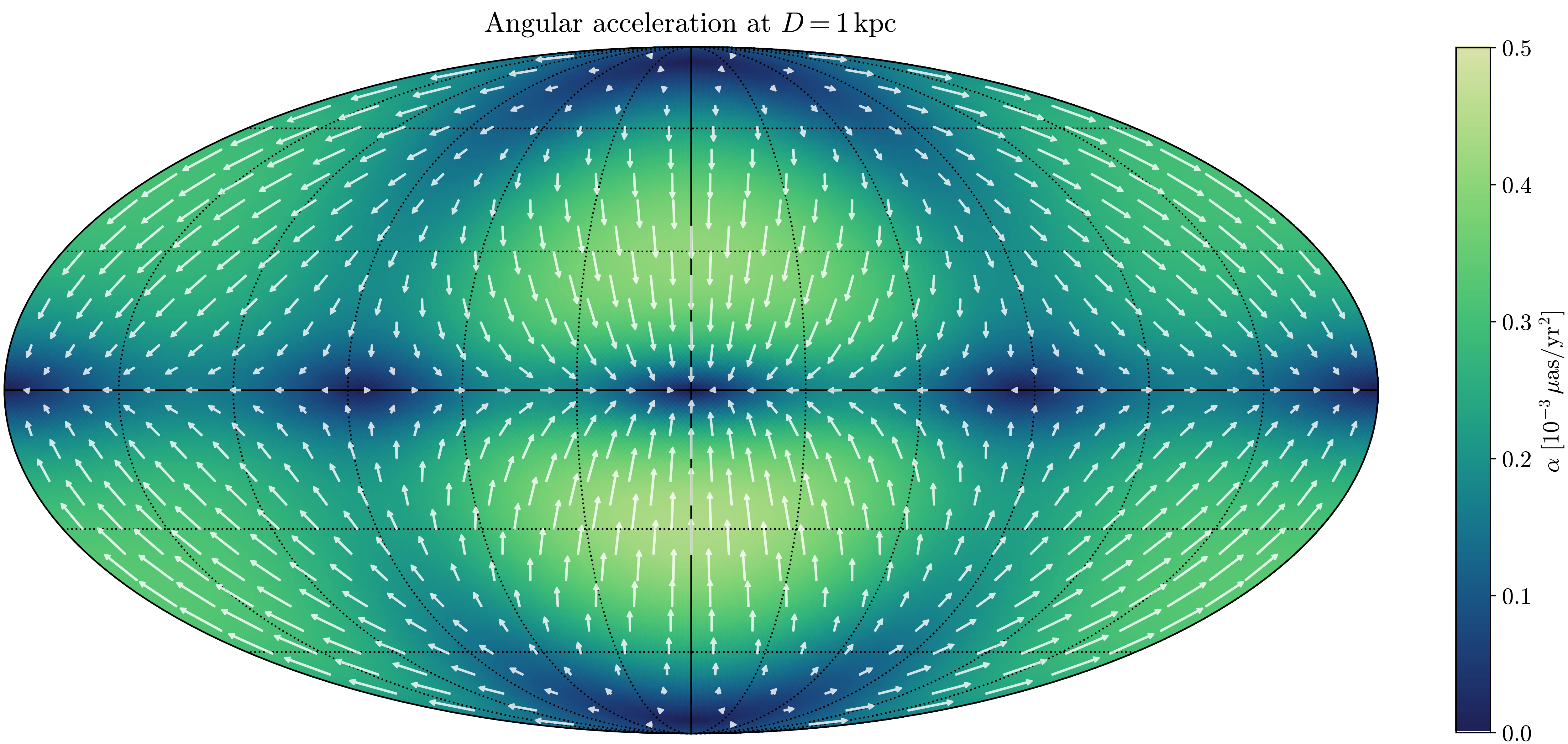






- . An astrometric precision per observation epoch of 3 × 10−13 achievable on bright binaries yielding component masses with a fractional precision at the 10−4 level
- Conceivably start to measure the mass loss rate a WR star at 10−4 M⊙/yr!

Applications: Galactic Accelerations



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

Conclusions

- Intensity Interferometry provides unprecedented relative astrometry measurements
- Technological improvements (fast single photon detectors) mean that we can measure sources many orders of magnitude fainter
- Simple but EPIC idea increases field of view to greatly extend capabilities without losing precision