Title: Extended-Path Intensity Correlation

Speakers: Ken Van Tilburg

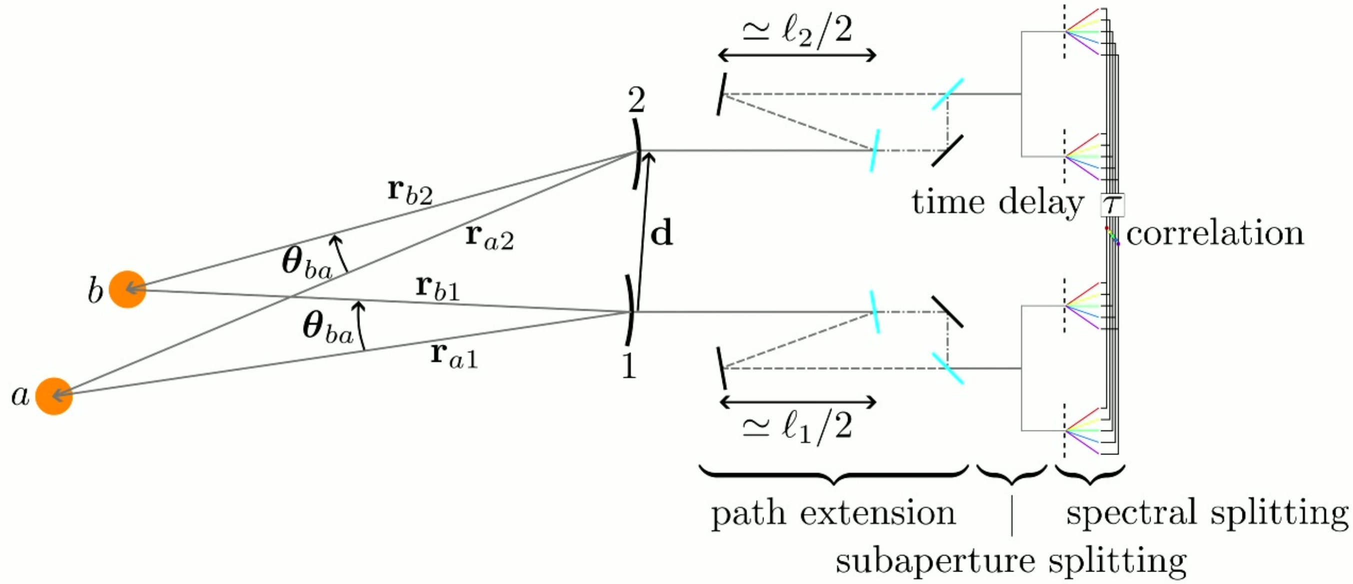
Collection/Series: Future Prospects of Intensity Interferometry

Subject: Cosmology

Date: November 01, 2024 - 11:10 AM

URL: https://pirsa.org/24110043

Extended-Path Intensity Correlation (EPIC)



Ken Van Tilburg CCPP @ NEW YORK UNIVERSITY | CCA @ FLATIRON INSTITUTE

with Marios Galanis (PI), Masha Baryakhtar (UW), Neal Weiner (NYU)

based on [arXiv:2307.03221] & [arXiv:2307.06989]

+work in progress with Nick Konidaris and Michael Rubel (Carnegie); David E Kaplan (JHU)

Future Prospects for Intensity Interferometry — Perimeter Institute, Nov 01, 2024

Image Morphology

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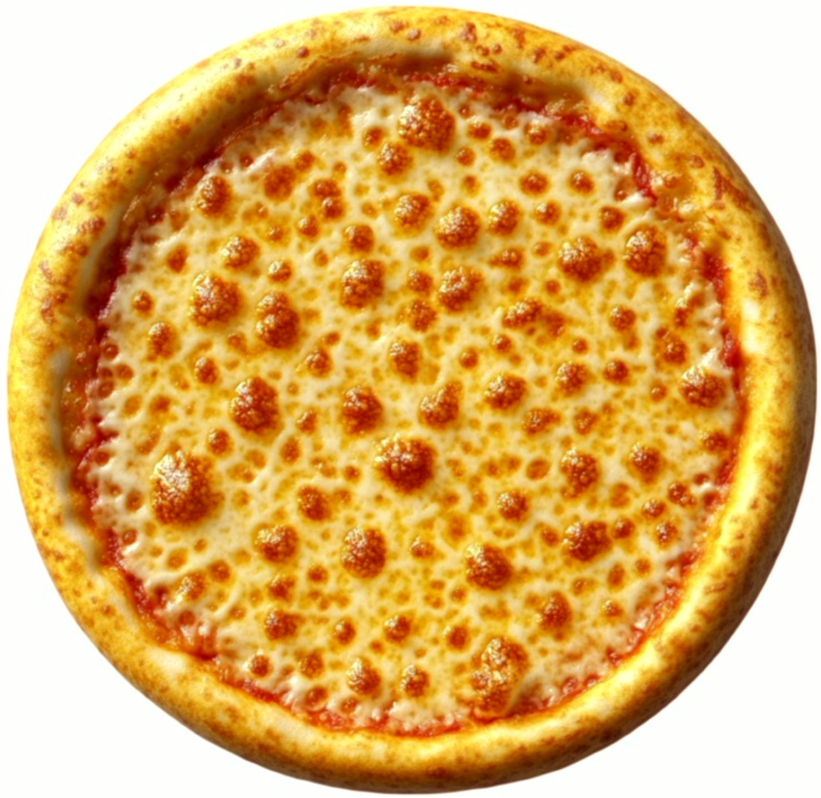
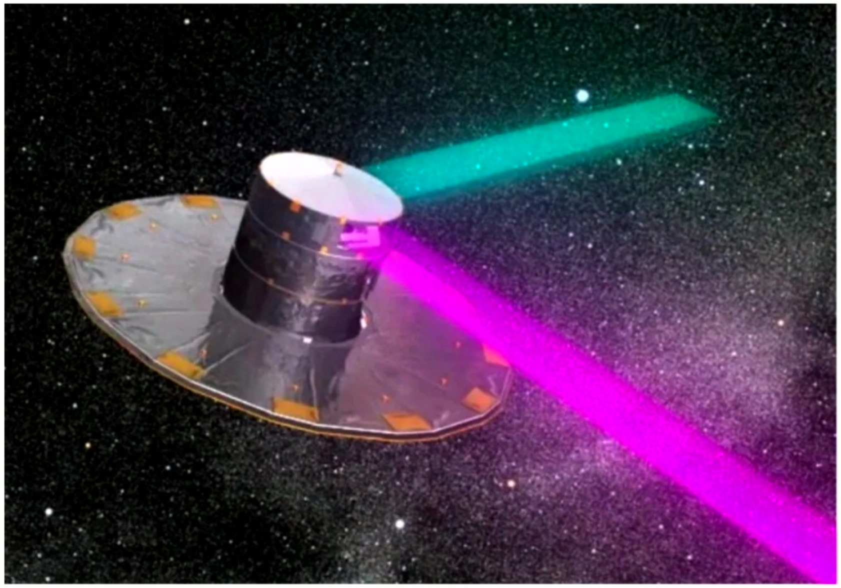
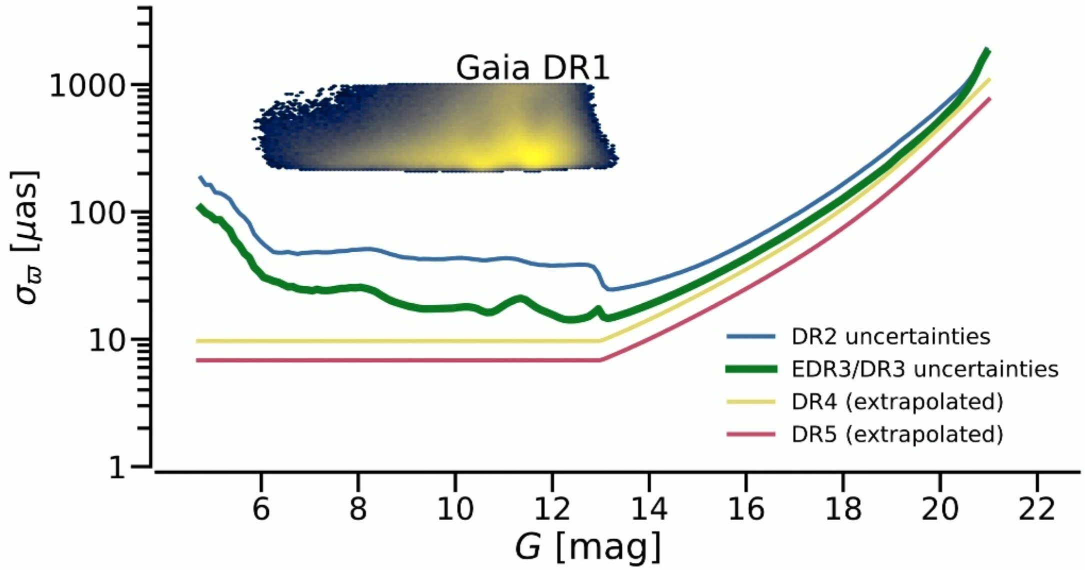


Astrometry

Astrometry with Space-Based “Imagers”

Gaia (2014–2024)





$$N_{\rm stars} \sim 2 \times 10^9$$

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

$$\sigma_{\delta\theta} \sim 100\,\mu\text{as}$$

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

Extended-Path Intensity Correlation (EPIC)

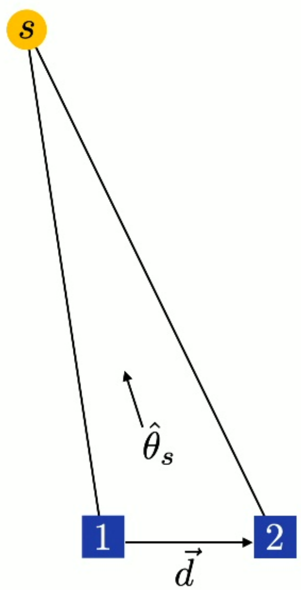
Astrometry with Intensity Interferometry

- basic idea
- problem
- **extended path innovation**
- projected performance

Scientific Applications

- binary orbits
- exoplanets
- stellar microlensing
- Galactic acceleration
- cosmic distance ladder
- quasar microlensing by DM substructure

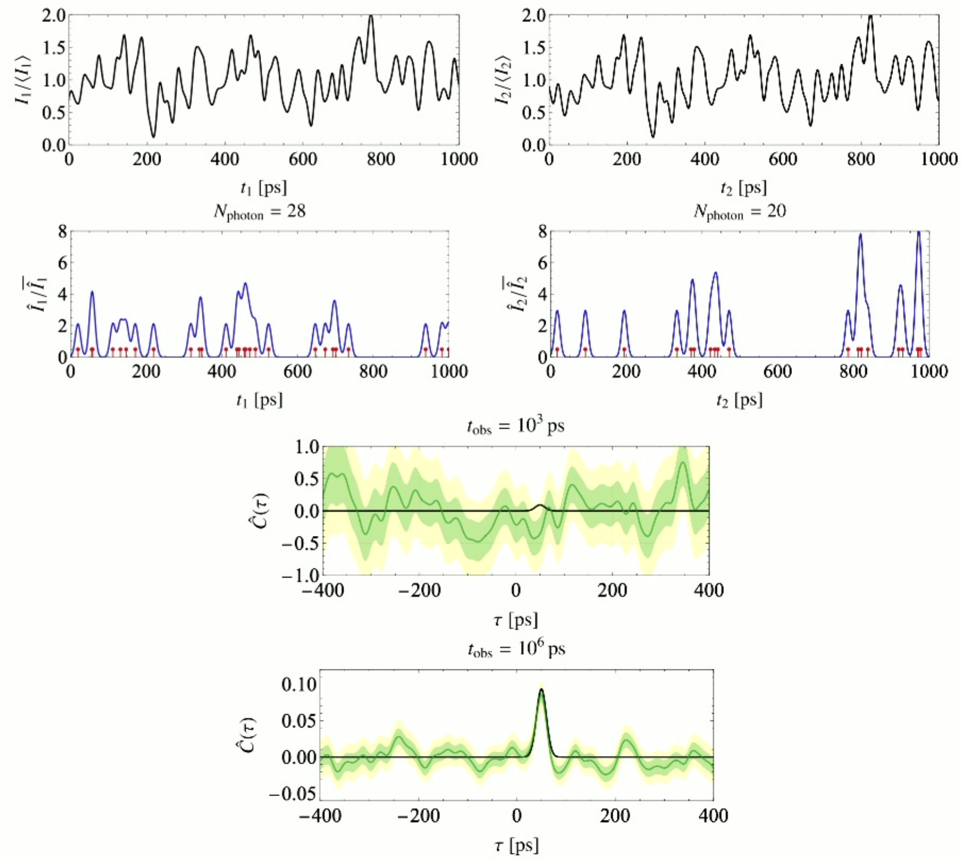
Astrometry with Intensity Interferometry



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

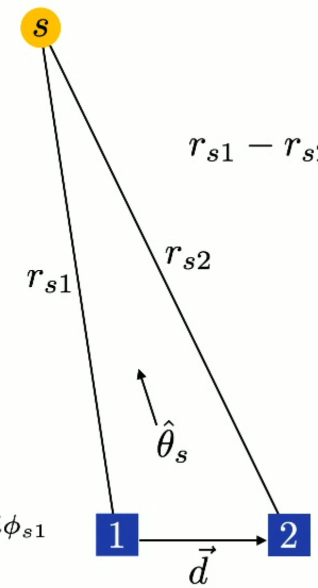
One Source

$\bar{\lambda} = 500\,\mathrm{nm}$ $R = 5{,}000$ $\sigma_t = 10\,\mathrm{ps}$



Intensity Correlations

One Source



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

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

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

$$\begin{aligned} C &\equiv \frac{\langle I_1(t) I_2(t+\tau)\rangle}{\langle I_1\rangle \langle I_2\rangle} - 1 \\ &= \frac{\langle E_1(t) E_1^*(t) E_2(t+\tau) E_2^*(t+\tau)\rangle}{\langle E_1 E_1^*\rangle \langle E_2 E_2^*\rangle} - 1 \\ &\simeq \frac{1}{\sqrt{2}\sigma_k \sigma_t} \exp\left\{ -\frac{(\tau + \hat{\theta}_s \cdot \vec{d})^2}{2\sigma_t^2} \right\} \end{aligned}$$

$$\sigma_{\hat{\theta}} \sim \frac{1}{\mathrm{SNR}} \frac{\sigma_t}{d} \sim \frac{10\,\mathrm{mas}}{\mathrm{SNR}} \left(\frac{\sigma_t}{10\,\mathrm{ps}}\right) \left(\frac{100\,\mathrm{km}}{d}\right)$$

Astrometry with Space-Based "Imagers"

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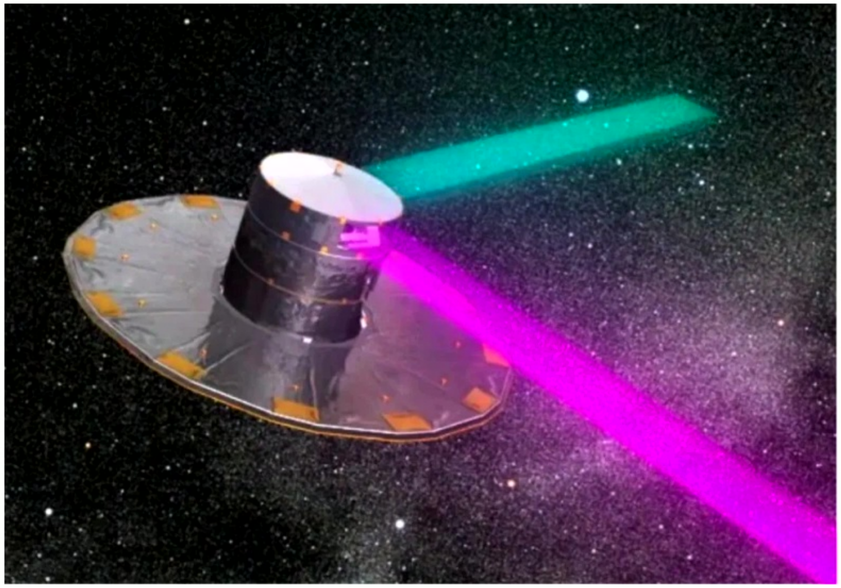

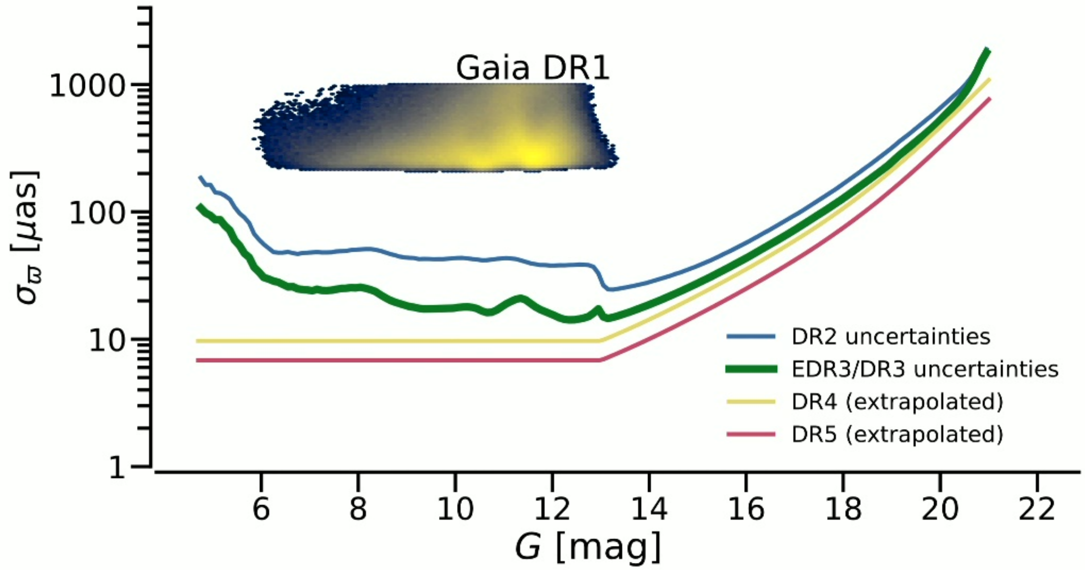

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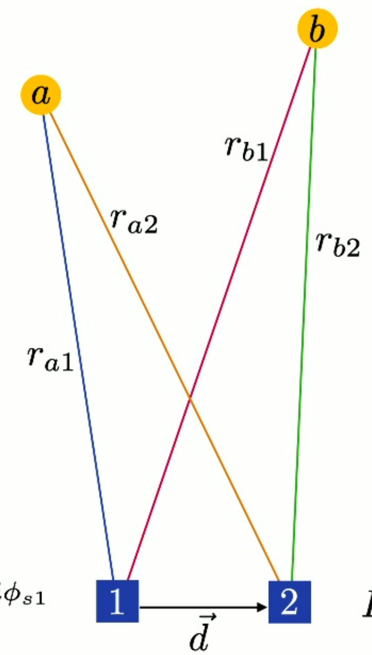
Intensity Correlations

Two Sources



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

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

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

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

$$\sigma_{\theta_{\mathrm{res}}} \sim \frac{\lambda}{d} \sim \underbrace{10^{-11}\,\mathrm{rad}}_{2\,\mu\mathrm{as}} \left(\frac{\lambda}{500\,\mathrm{nm}}\right) \left(\frac{10\,\mathrm{km}}{d}\right)$$

Intensity Correlations

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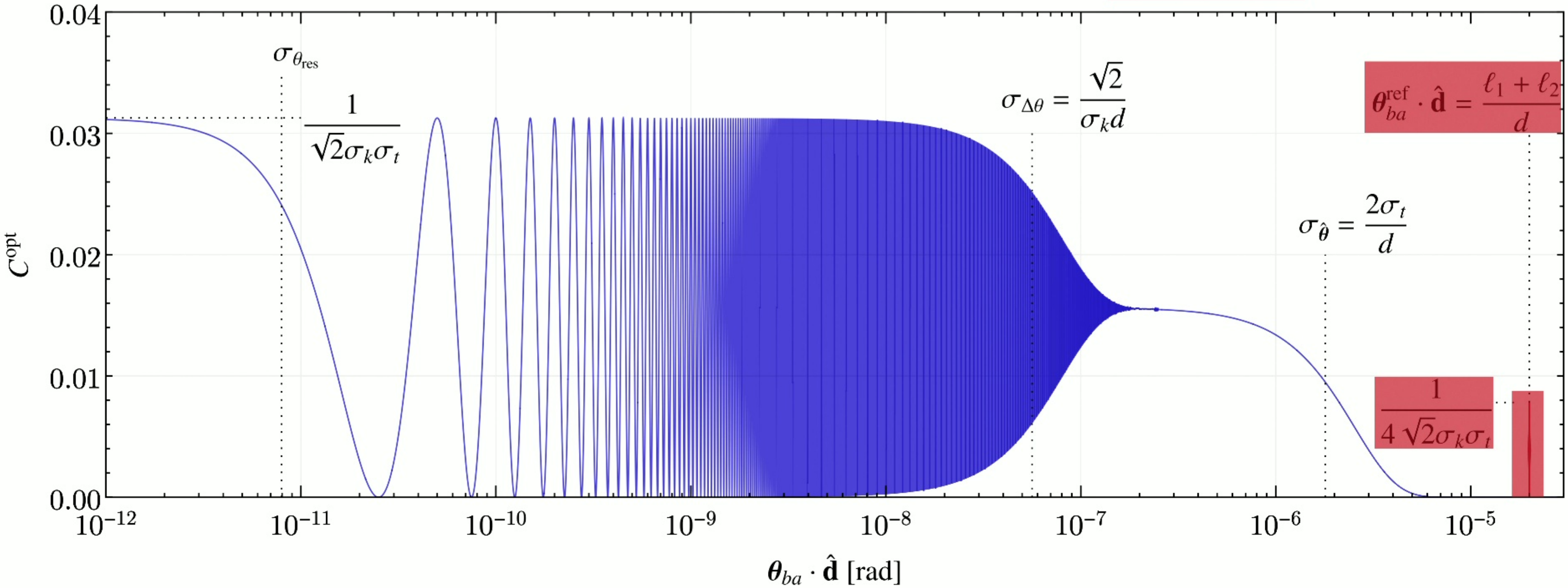
Two Sources

$d = 10\,\text{km},\ \bar{\lambda} = 500\,\text{nm}, \mathcal{R} = 5{,}000,\ \sigma_t = 30\,\text{ps},\ \widetilde{I}_a = \widetilde{I}_b = 1/2,\ \ell_1 = \ell_2 = 10\,\text{cm}$



Intensity Correlations

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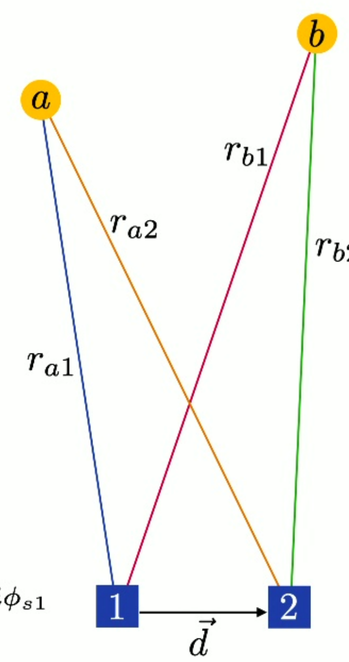

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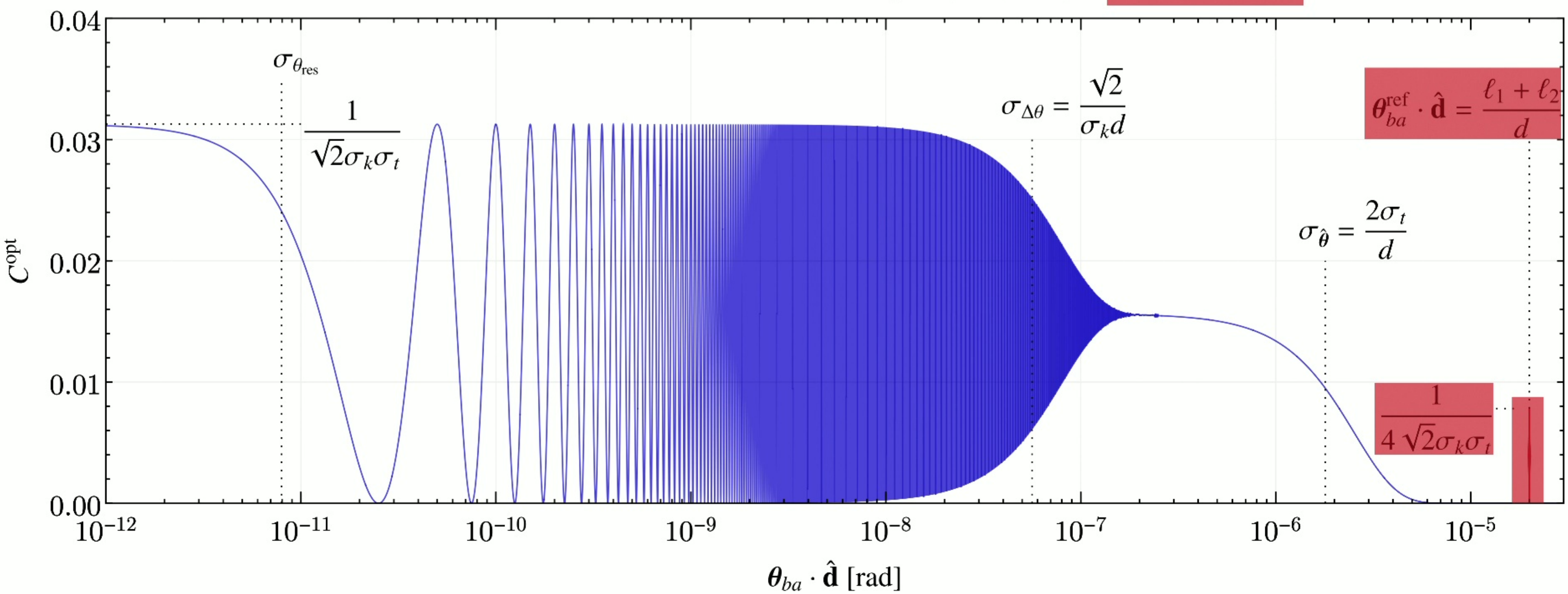
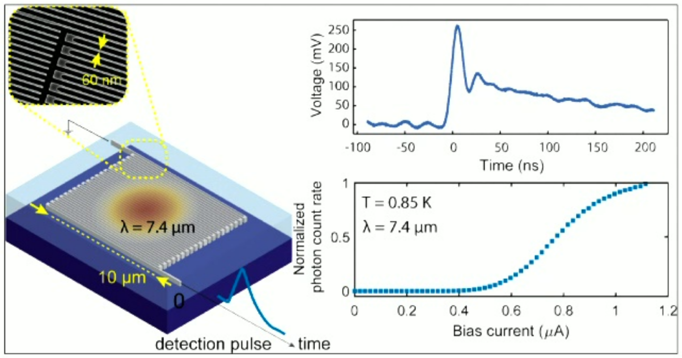
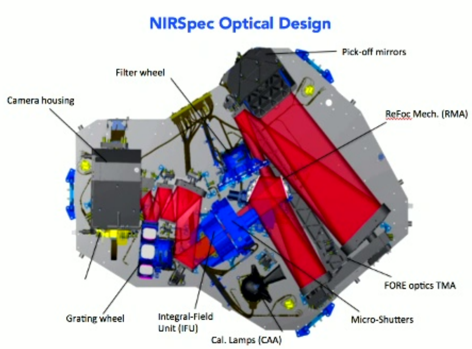


Limitations

Signal-to-Noise Ratio



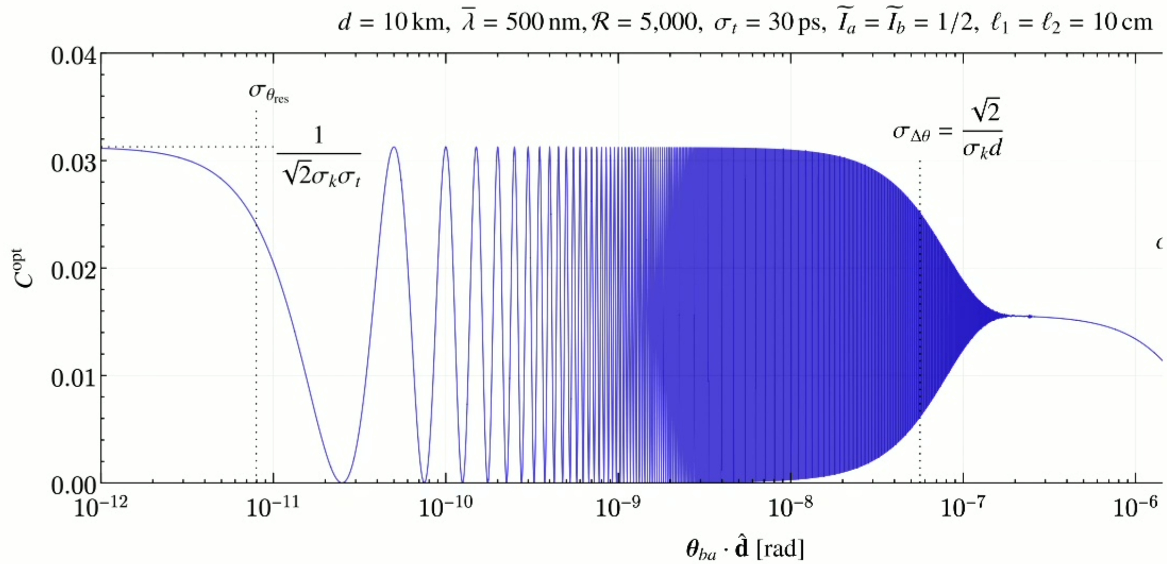
Fast Single-Photon Detection



Multi-Channel Spectroscopy

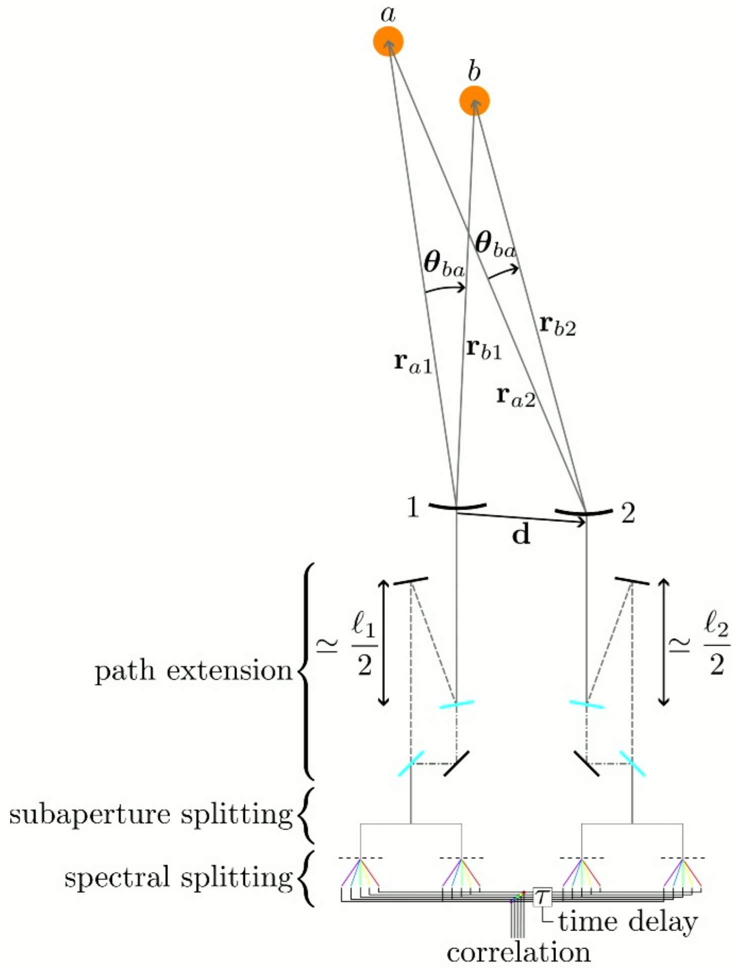
Field of View

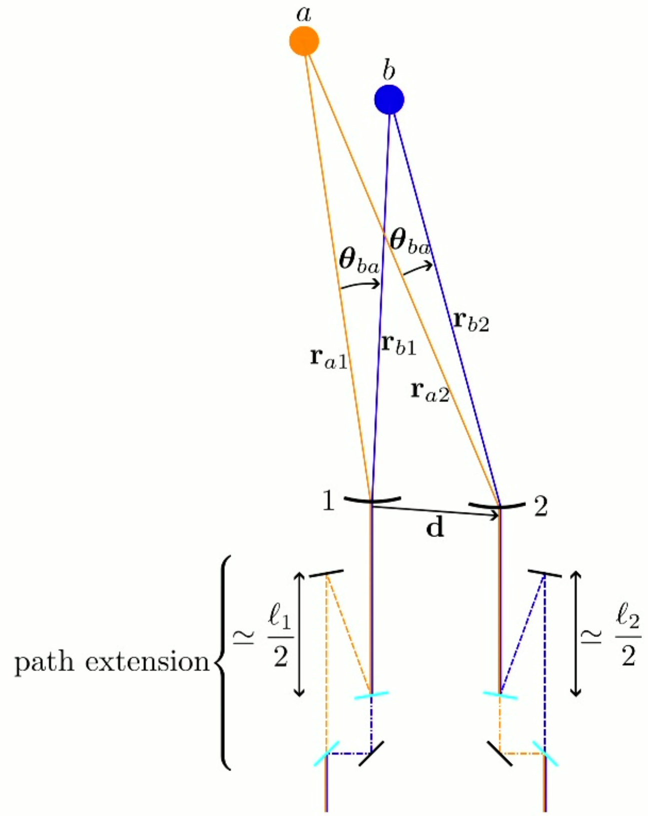
$$\sigma_{\Delta\theta} \sim \underbrace{\mathcal{R}}_{k/\sigma_k} \sigma_{\theta_{\rm res}} \sim \underbrace{5 \times 10^{-8}\,\text{rad}}_{10\,\text{mas}} \left(\frac{\mathcal{R}}{5{,}000}\right)\left(\frac{\lambda}{500\,\text{nm}}\right)\left(\frac{10\,\text{km}}{d}\right)$$



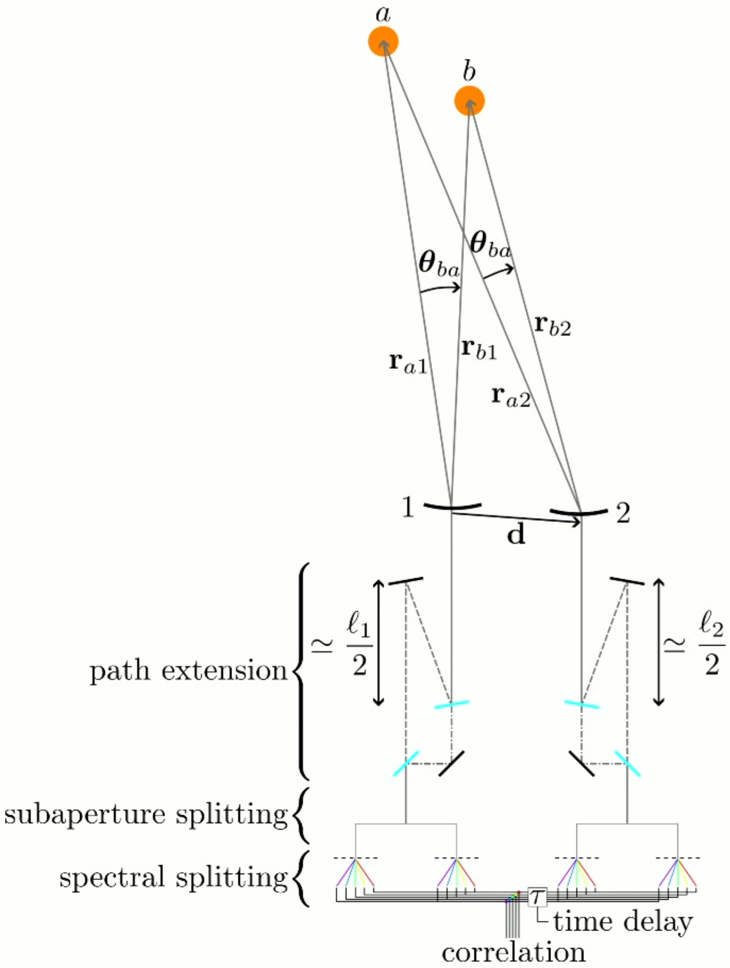
Extended Path

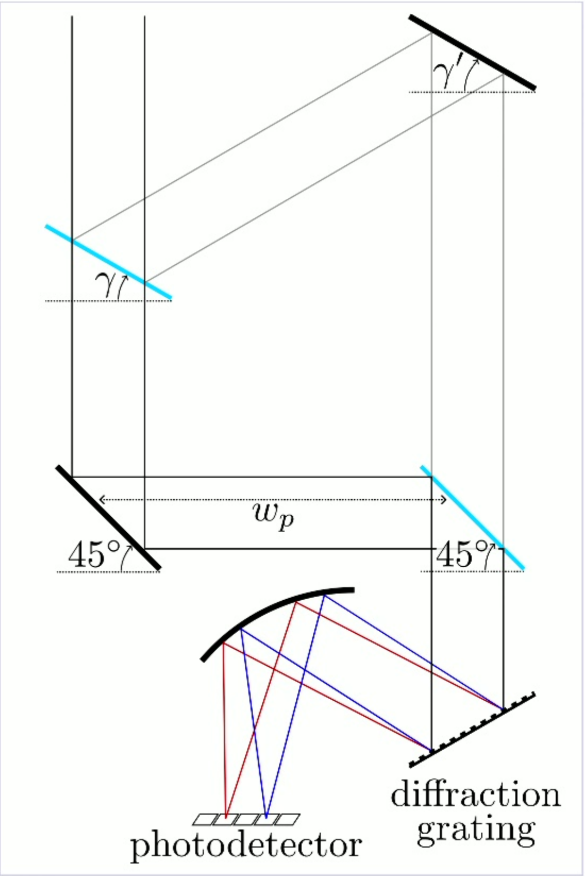
Extended-Path Intensity Correlation





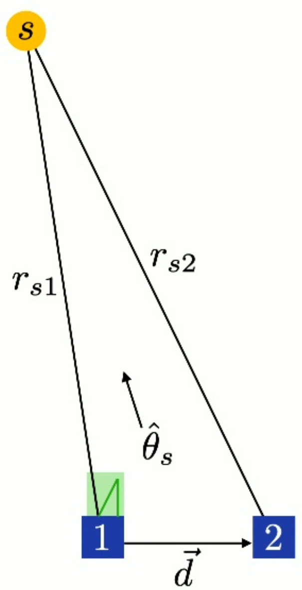
Extended-Path Intensity Correlation

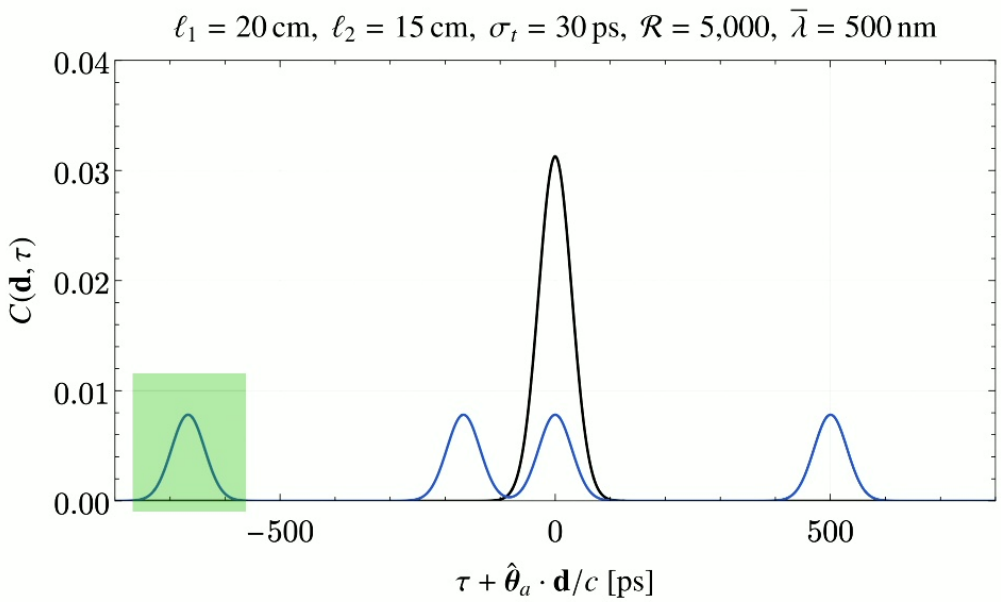


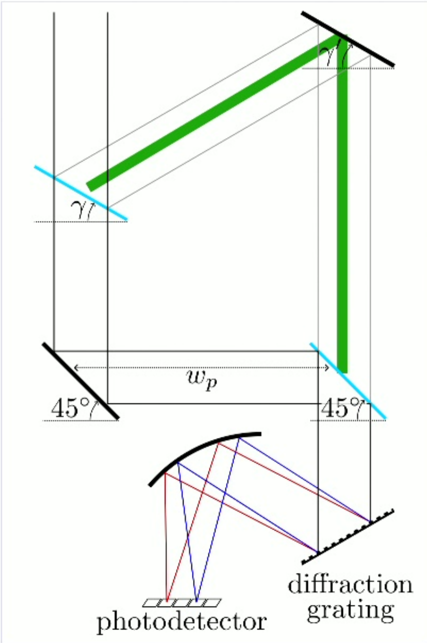


Extended-Path Intensity Correlation

One Source







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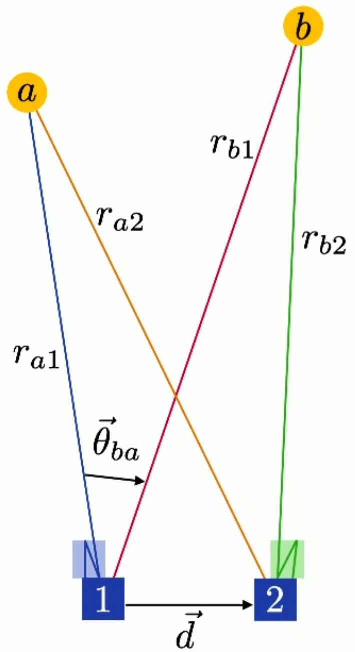
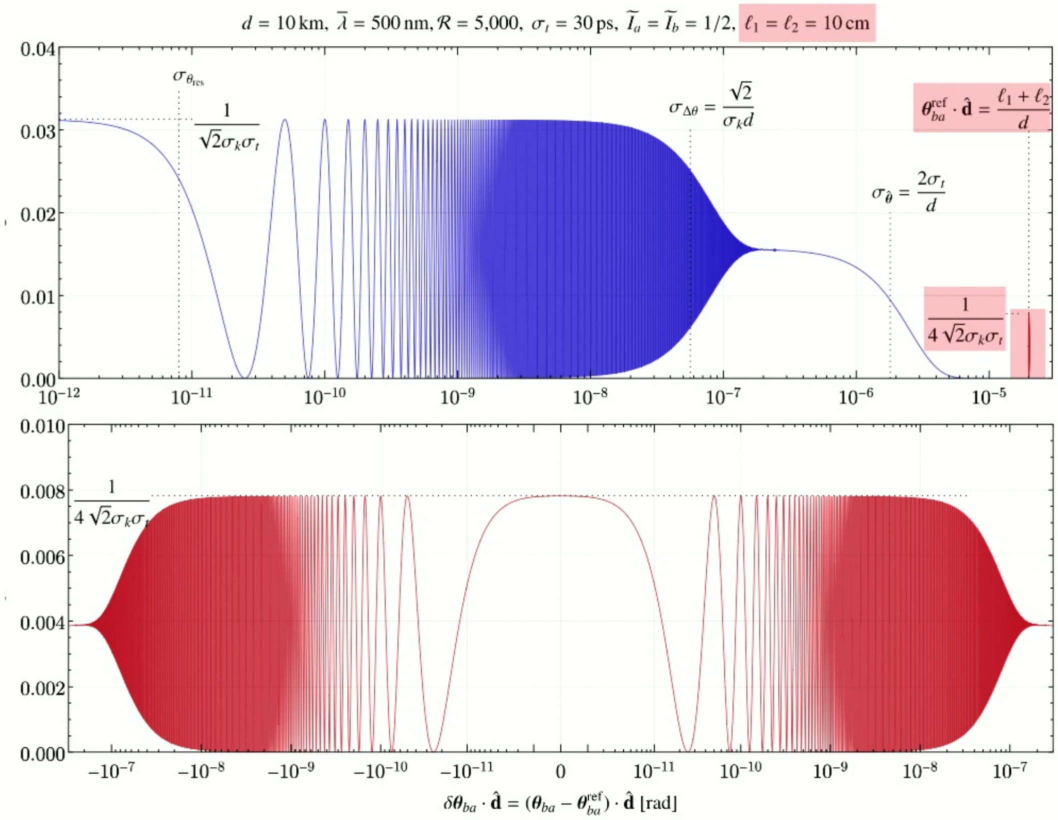
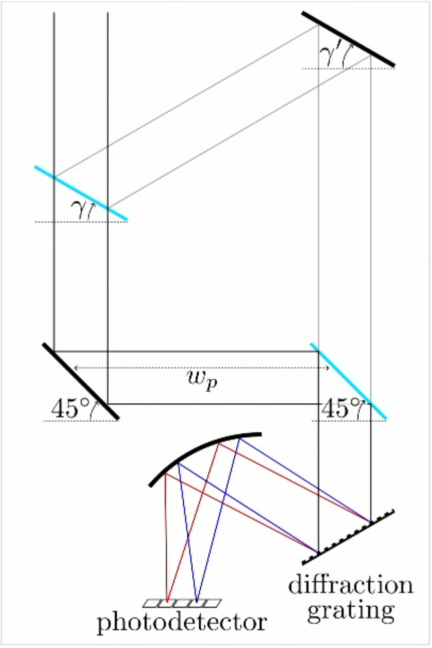






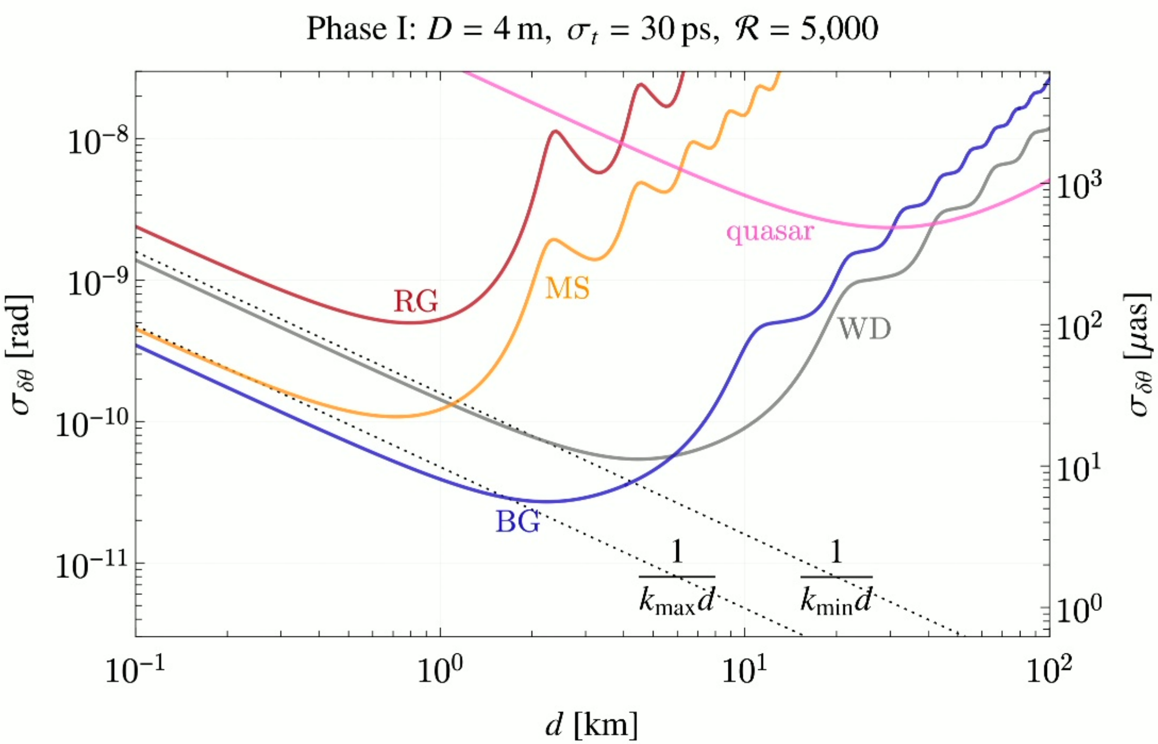
Future Phases of EPIC

	D	σ_t	$\mathcal{R}$	n_{arr}	$\sigma_{\delta\theta}$ [μas]	$\sigma_{\hat{\boldsymbol{\theta}}}$ [arcsec]	$\sigma_{\Delta\theta}$ [arcsec]
Phase I	4 m	30 ps	5,000	1	22.3	5.24	0.164
Phase II	10 m	10 ps	10,000	1	1.46	1.75	0.327
Phase III	10 m	3 ps	20,000	10	0.0564	0.524	0.656

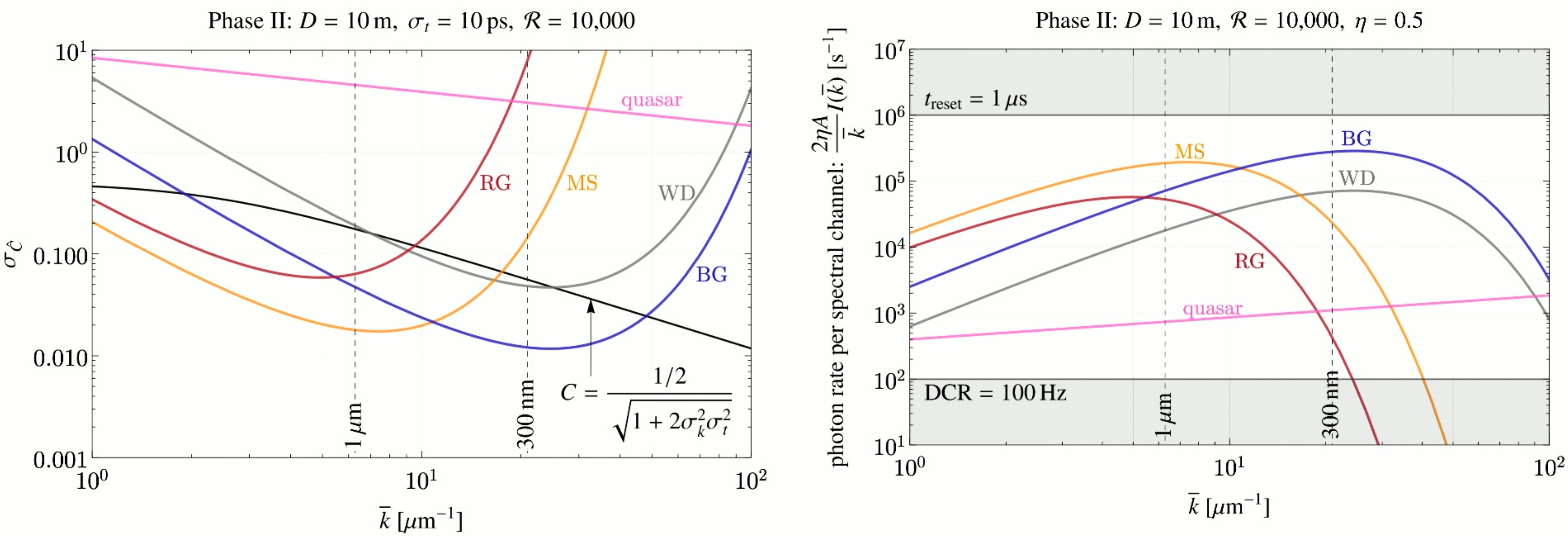
Light-Centroiding Precision

$$\sigma_{\theta_{\rm res}} \sim \frac{\lambda}{d} \sim \underbrace{10^{-11}\,\mathrm{rad}}_{2\,\mu\mathrm{as}} \left(\frac{\lambda}{500\,\mathrm{nm}}\right)\left(\frac{10\,\mathrm{km}}{d}\right)$$

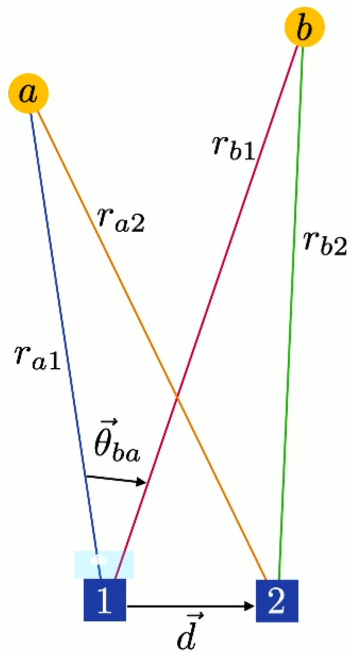
$$\sigma_{\delta\theta} \sim \frac{1}{\sqrt{N_1 N_2}} \frac{1}{Ad} \sqrt{\frac{\sigma_t}{t_{\rm shot}}} \sqrt{\frac{\sigma_k}{k}} \frac{1}{T_s^3 \theta_s^2}$$

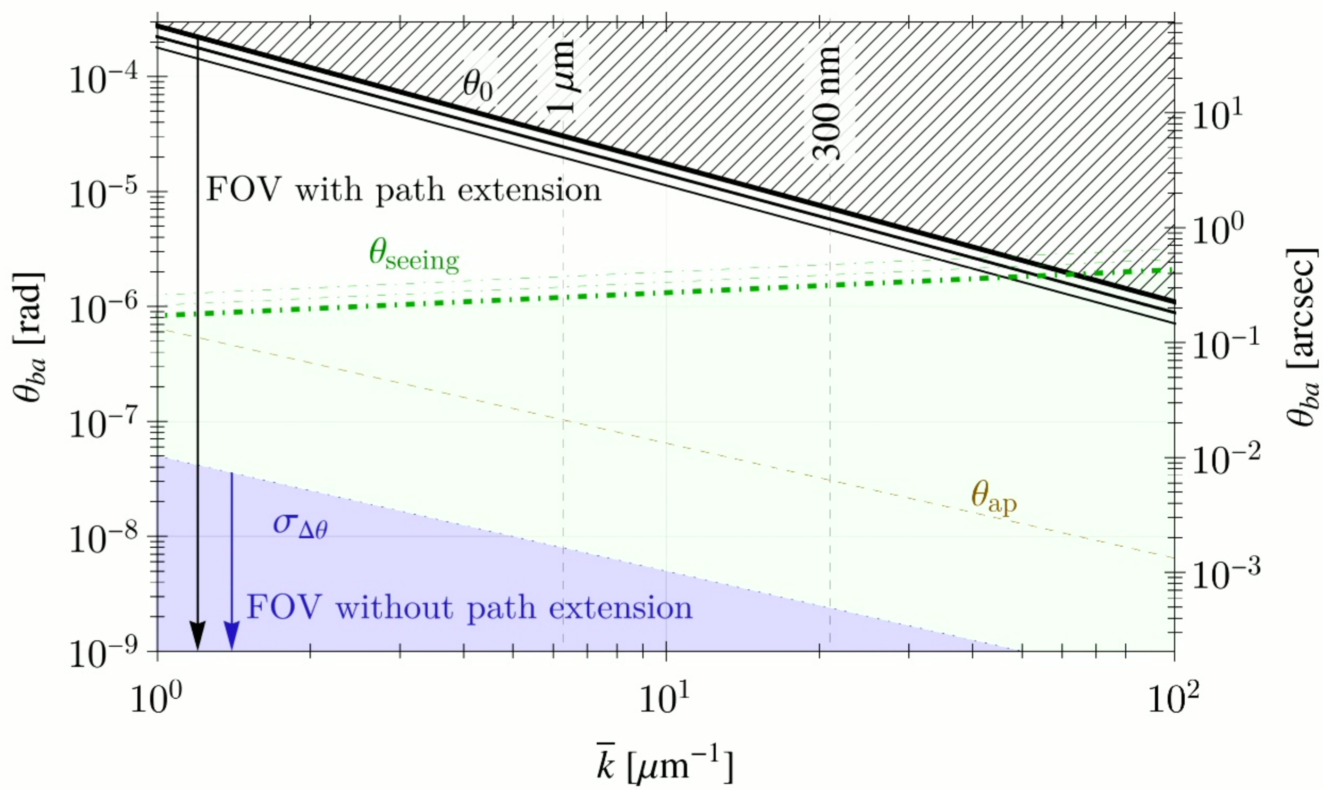


Signal-to-Noise Ratio



Atmospheric Aberrations





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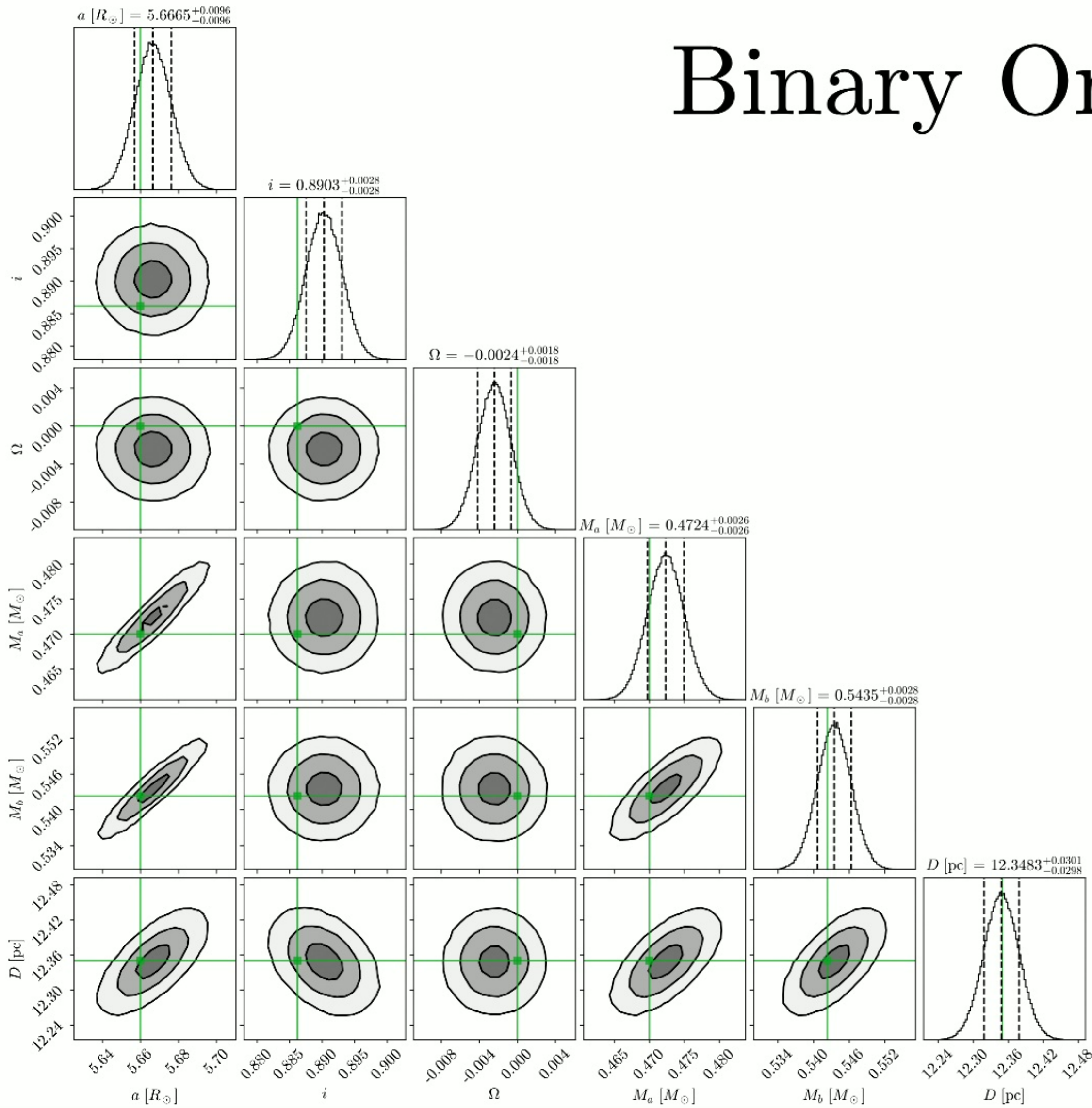
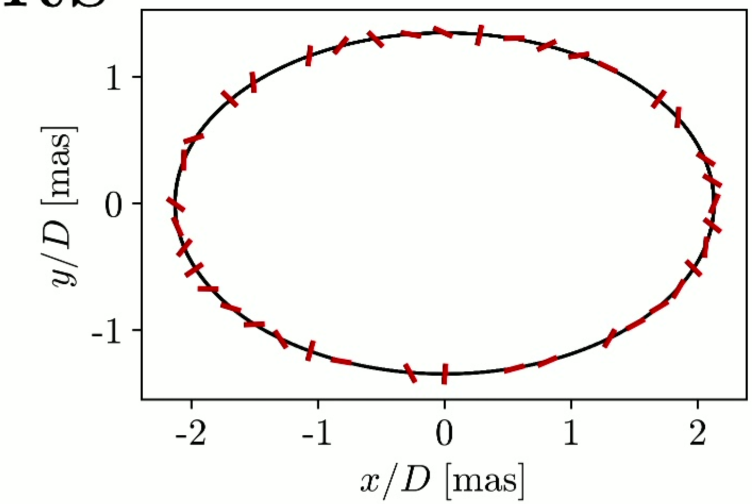
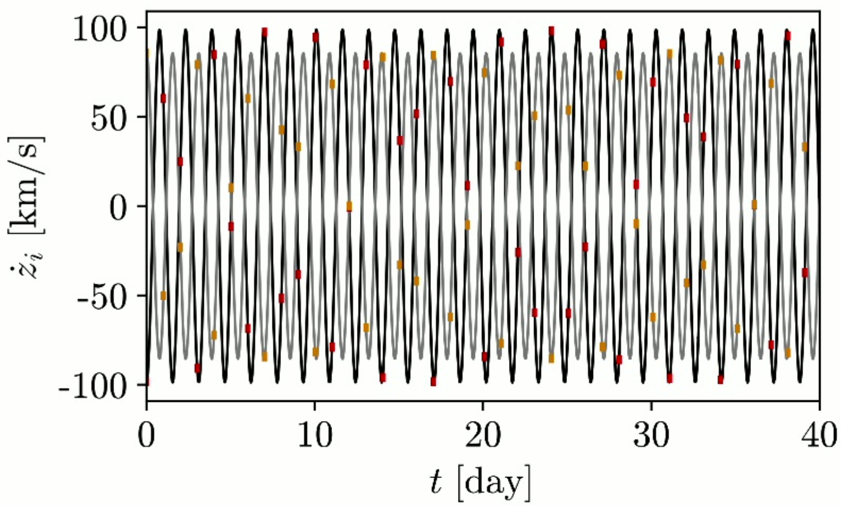
Binary Orbits

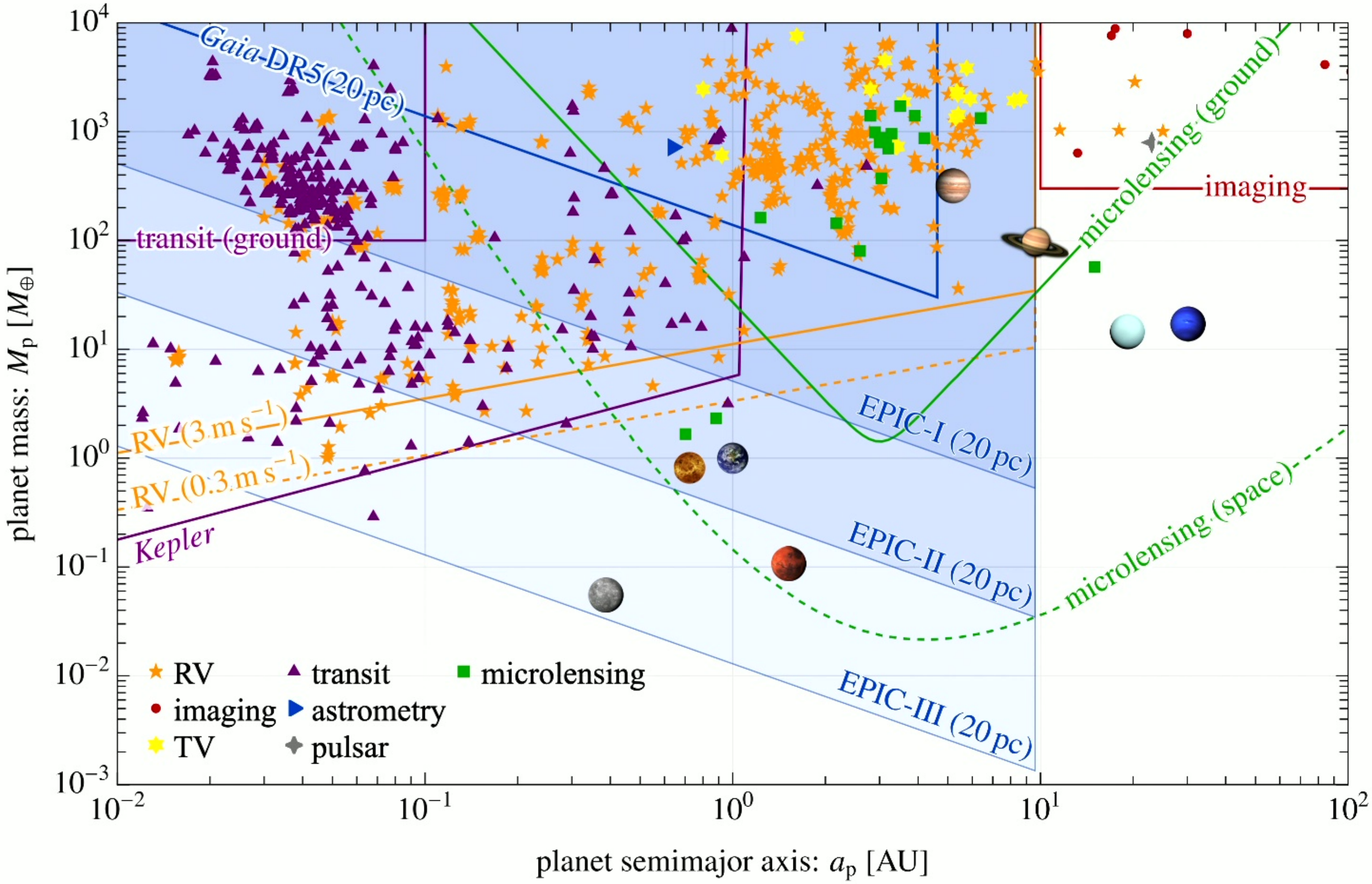




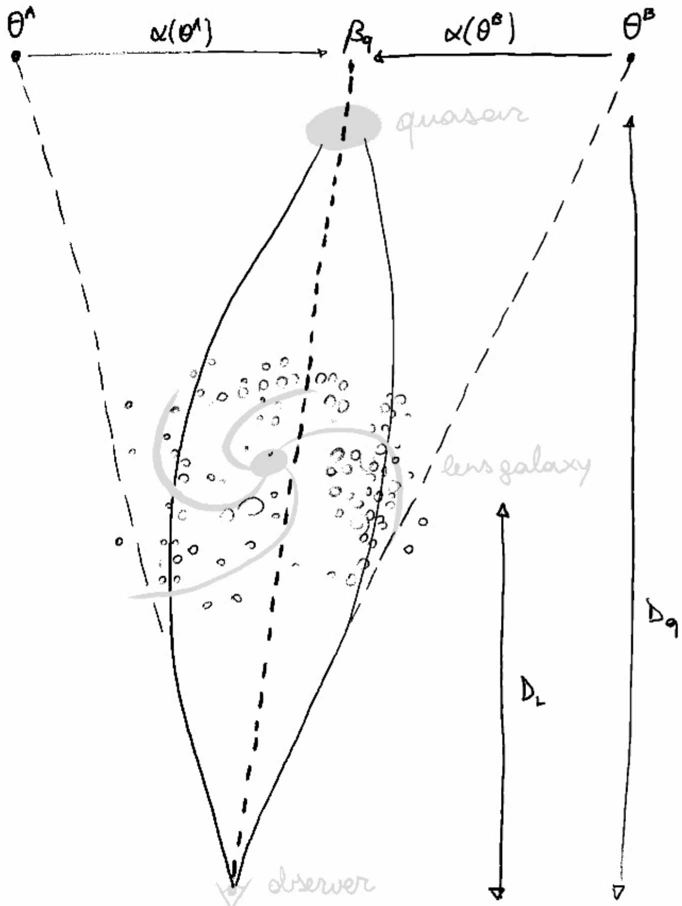


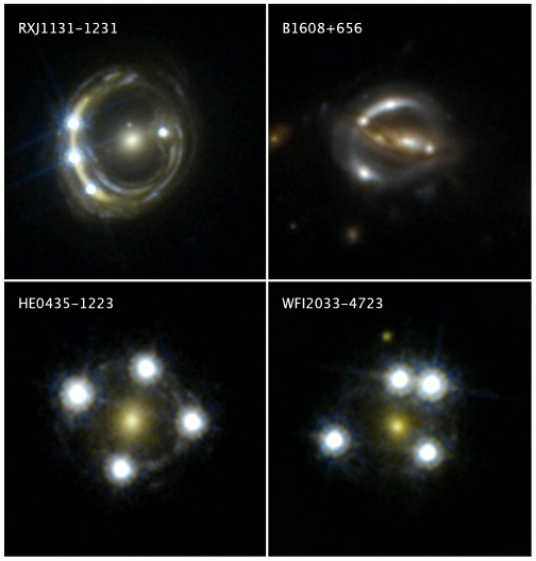
Exoplanets

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



Quasar Microlensing with David E Kaplan (JHU)

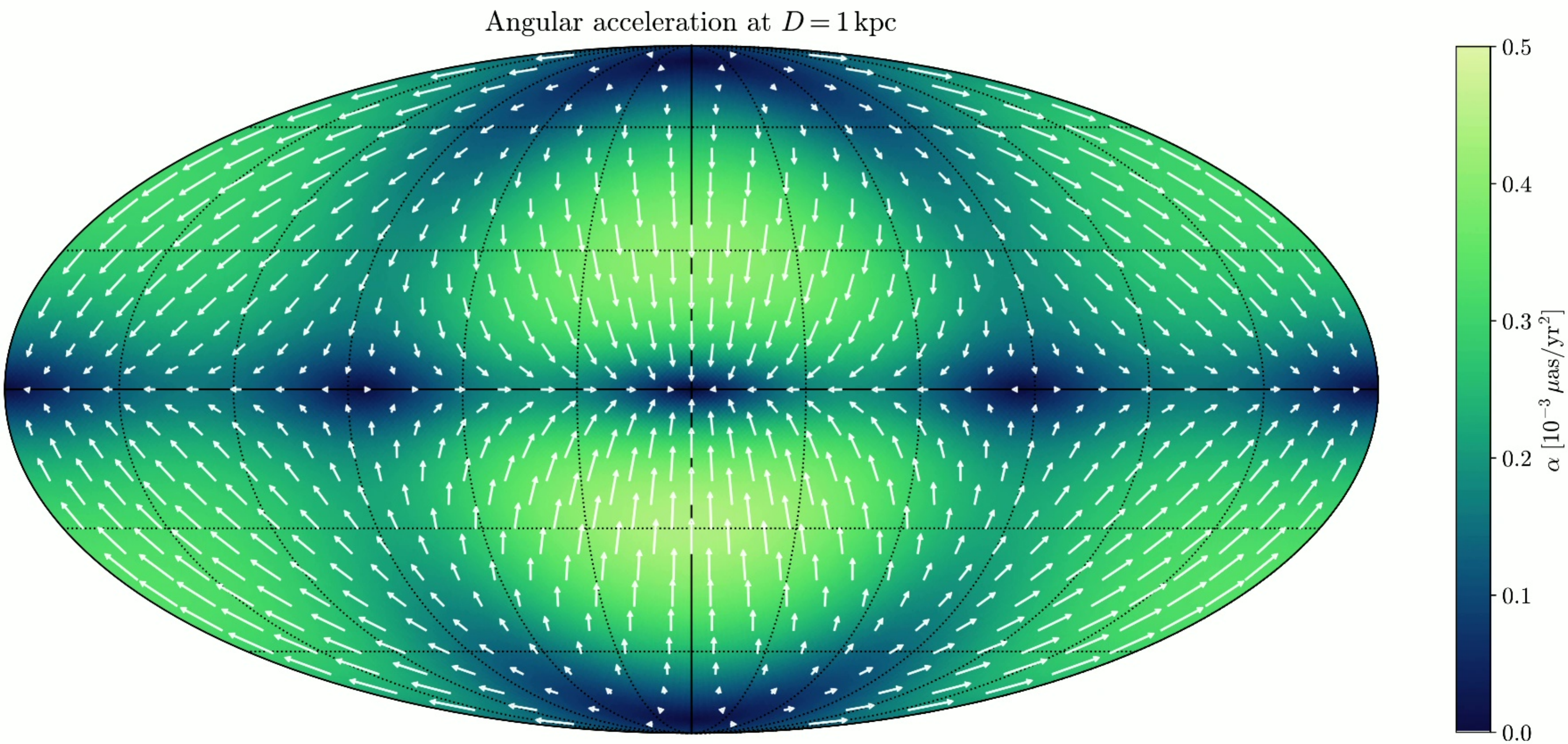




$$\theta_E = \sqrt{\frac{4GM_L}{D_L}\frac{D_{LS}}{D_S}} \sim 2\,\mu\text{as}\sqrt{\frac{M_L}{M_\odot}\frac{\text{Gpc}}{D_L}}$$

motion + stochastic noise: $\delta\theta^{\rm I} \sim B^{\rm I}\theta_E\sqrt{\kappa_L}$

Galactic Acceleration



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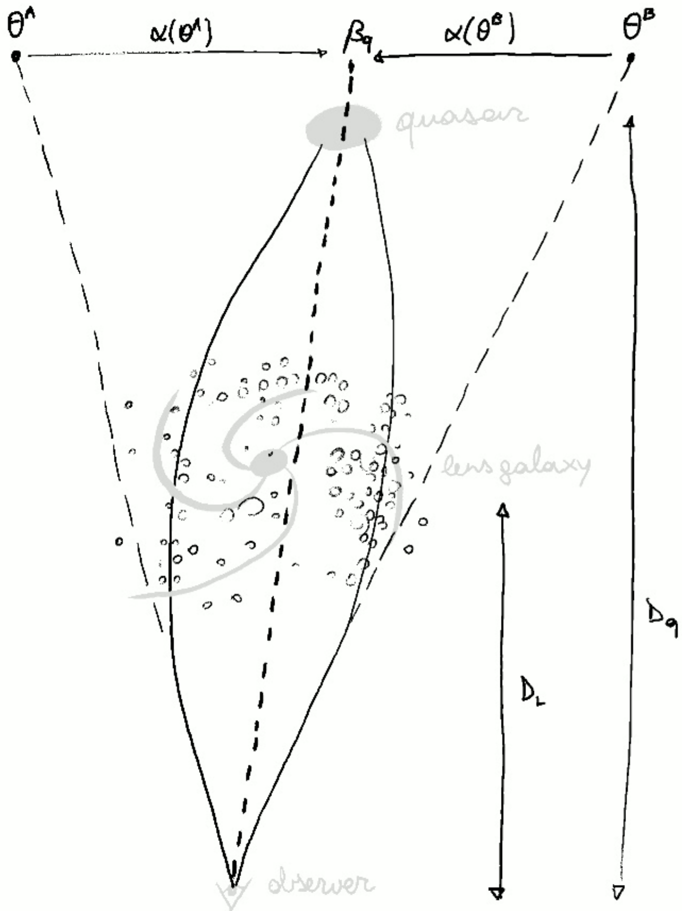

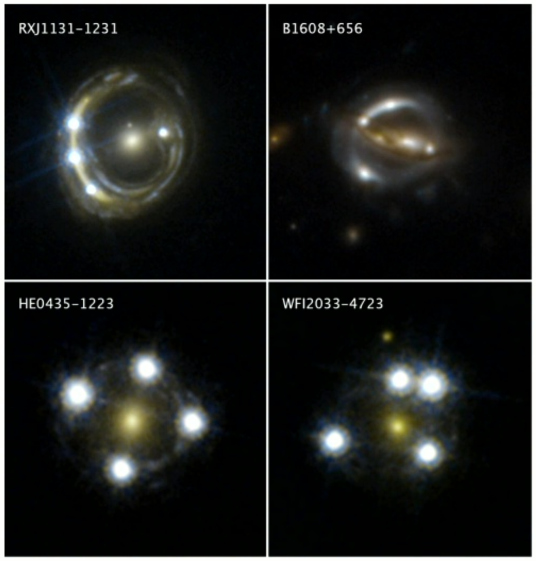

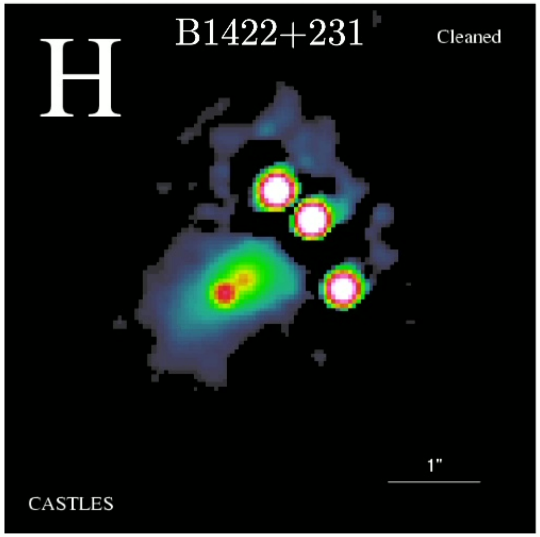

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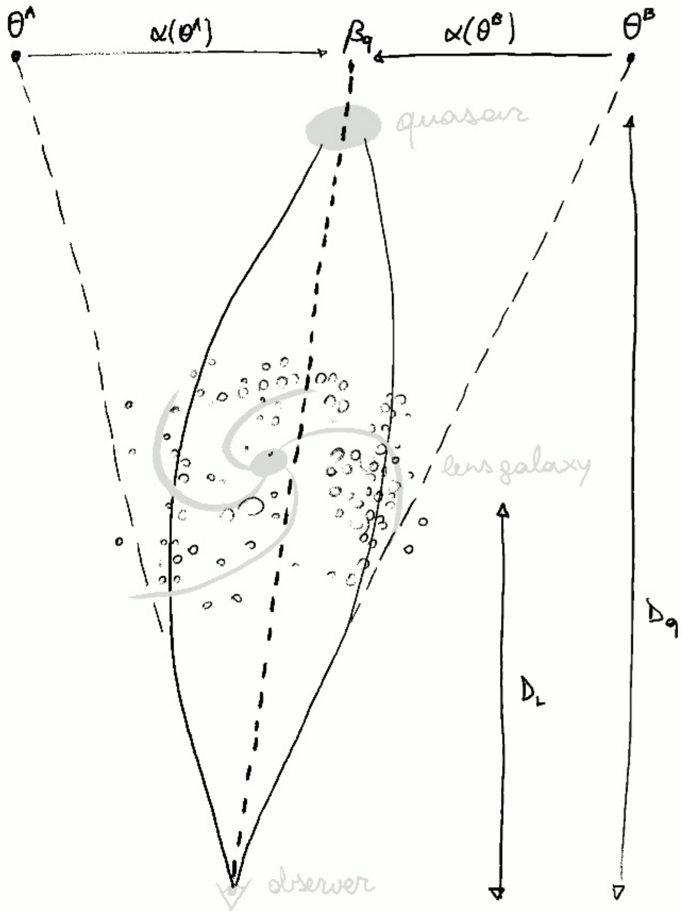

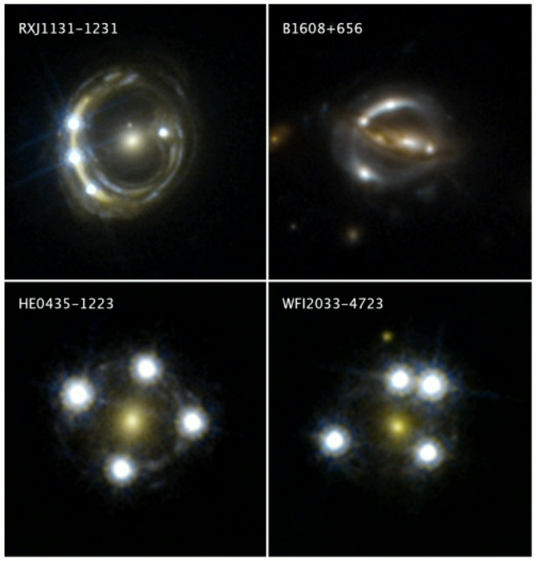

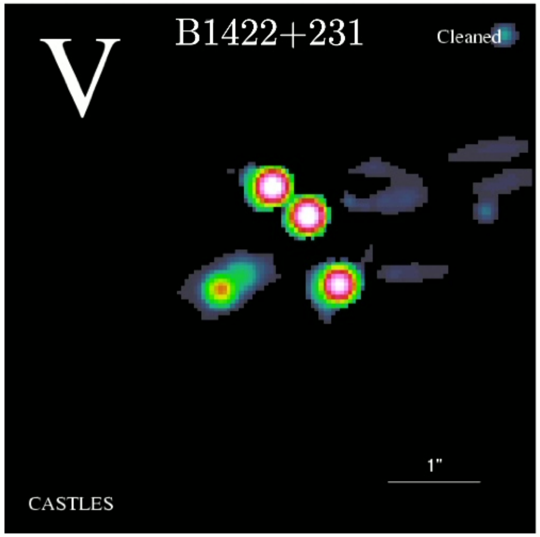

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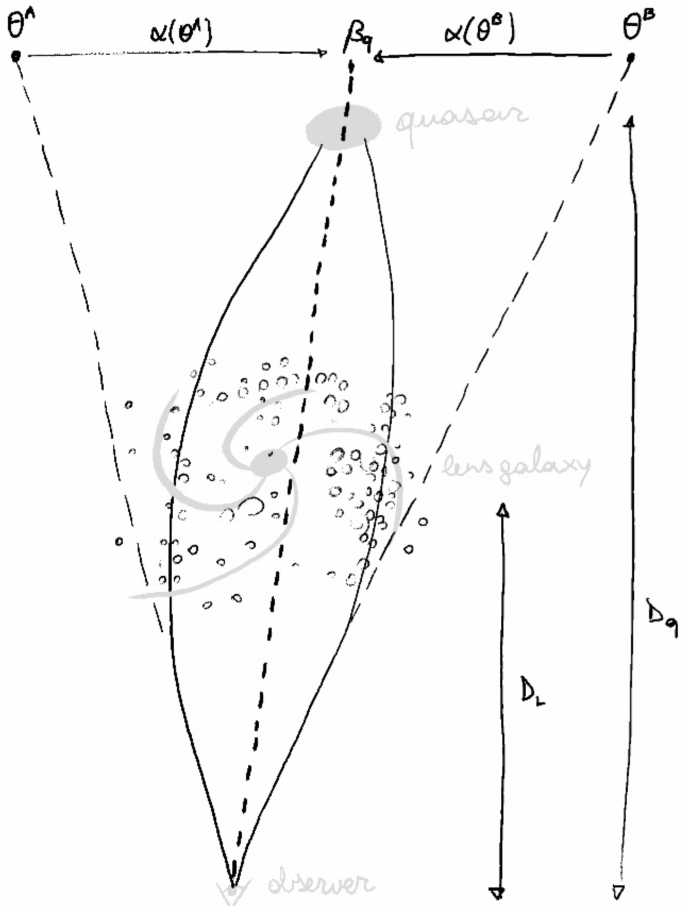

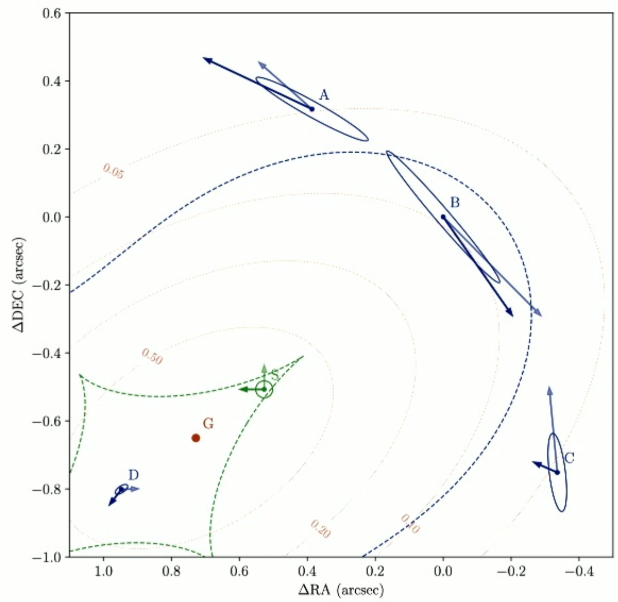

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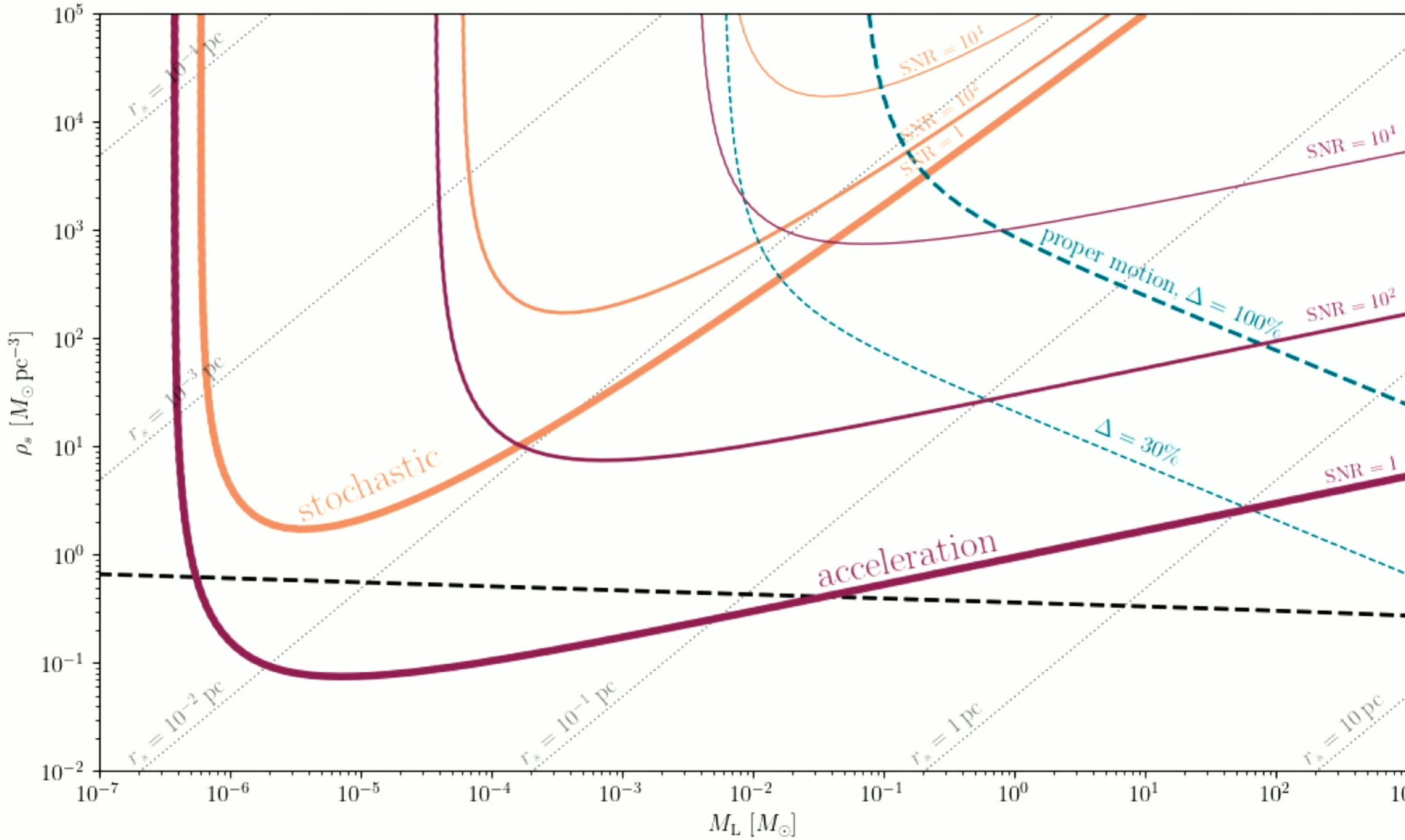
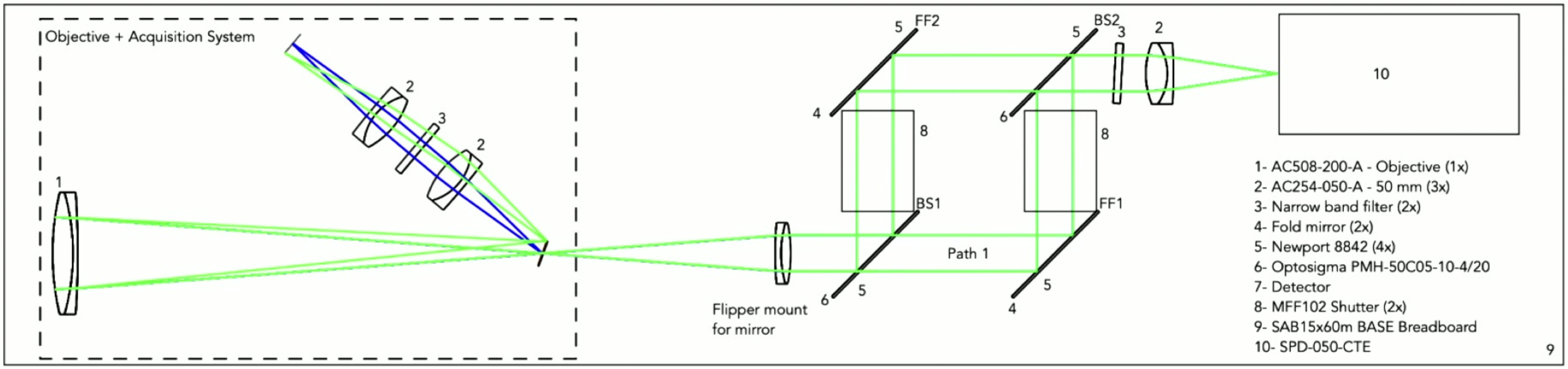
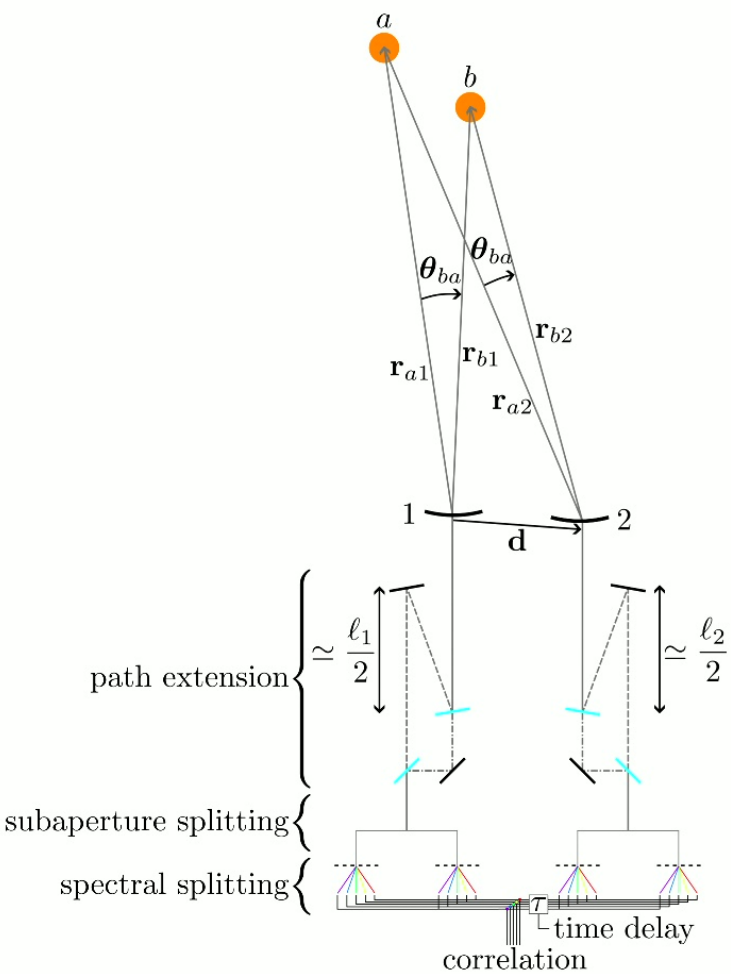


Experimental Directions

EPIC Demonstration with Nick Konidaris, Michael Rubel (Carnegie)





Conclusions

sub-μas resolution and even better *differential* light-centroiding precision

on sources separated by less than a few arcseconds

new astrophysical applications

fundamental cosmic measurements

dark matter substructure at sub-stellar masses

"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*