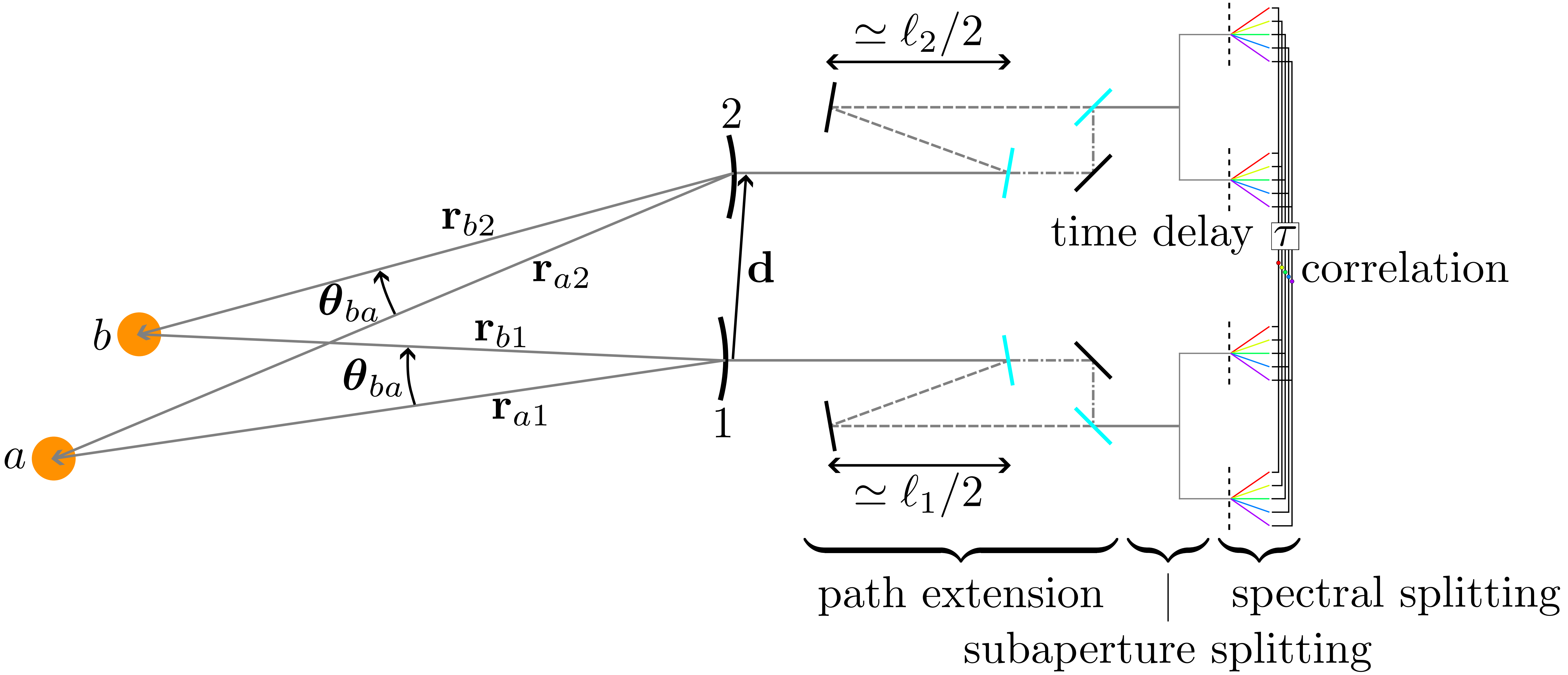
Extended Path Intensity Correlation (EPIC)



Ken Van Tilburg CCPP @ New York University | CCA @ Flatiron Institute

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

based on [arXiv:2306.XXXXX]

Stellar Intensity Interferometry Workshop — OSU CCAPP — May 23, 2023

Outline

1. Introduction to Astrometry

2. Intensity Interferometry

3. Scientific Applications

Outline

1. Introduction to Astrometry

- eye balls and imaging telescopes
- spectrographs
- amplitude interferometers

2. Intensity Interferometry

3. Scientific Applications

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- basic idea
- extended path invention
- projected performance
- technical details

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

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Astrometry

= measurements of the positions and movements of stars / celestial bodies

global astrometric precision: $\sigma_{\hat{\theta}}^{\text{astrolabe}} \approx 20\,\text{arcmin} \approx 6 \times 10^{-3}\,\text{rad}$

angular resolution: $\sigma_{\theta_{\text{res}}}^{\text{eye}} \approx 1\,\text{arcmin} \approx 3 \times 10^{-4}\,\text{rad}$

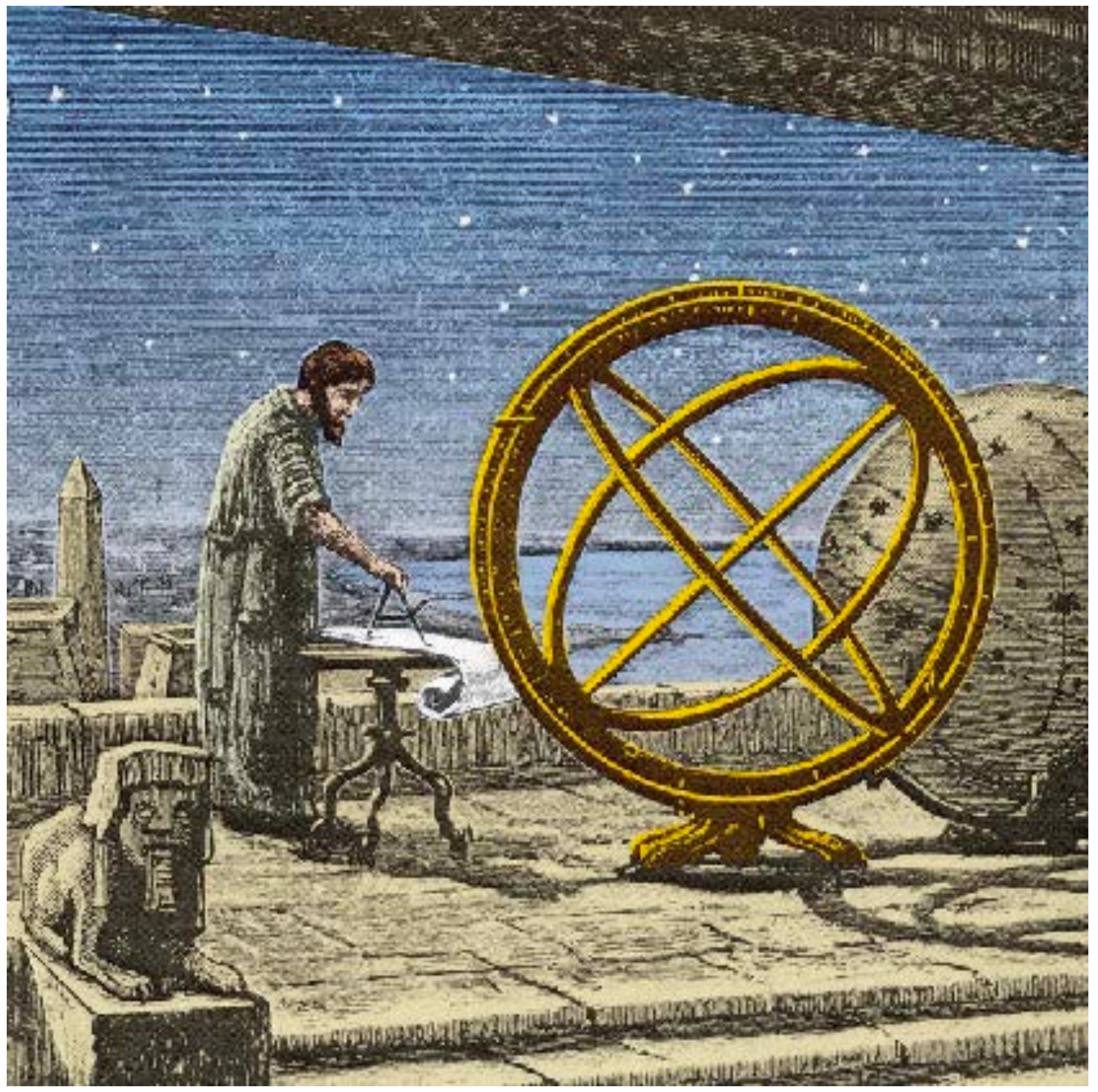
$\sigma_{\hat{\theta}}^{\text{mural}} \approx 30\,\text{arcsec}$

$\approx 1.5 \times 10^{-4}\,\text{rad}$

trigonometry

Earth's precession

astrolabe



Hipparchus (190—120 BC)

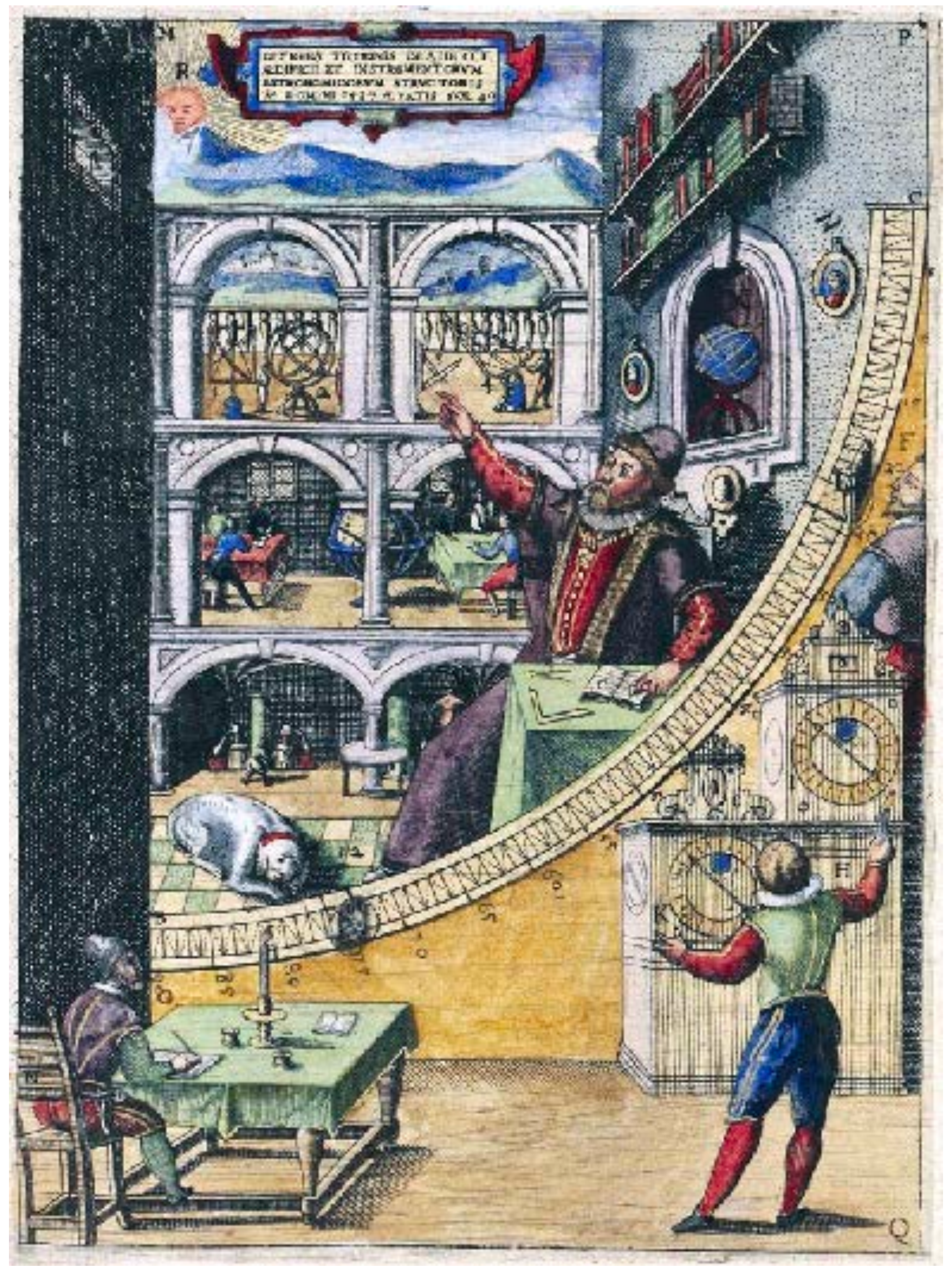
catalogue of 1022 stars

[Almagest]

Ptolemy (100–170)

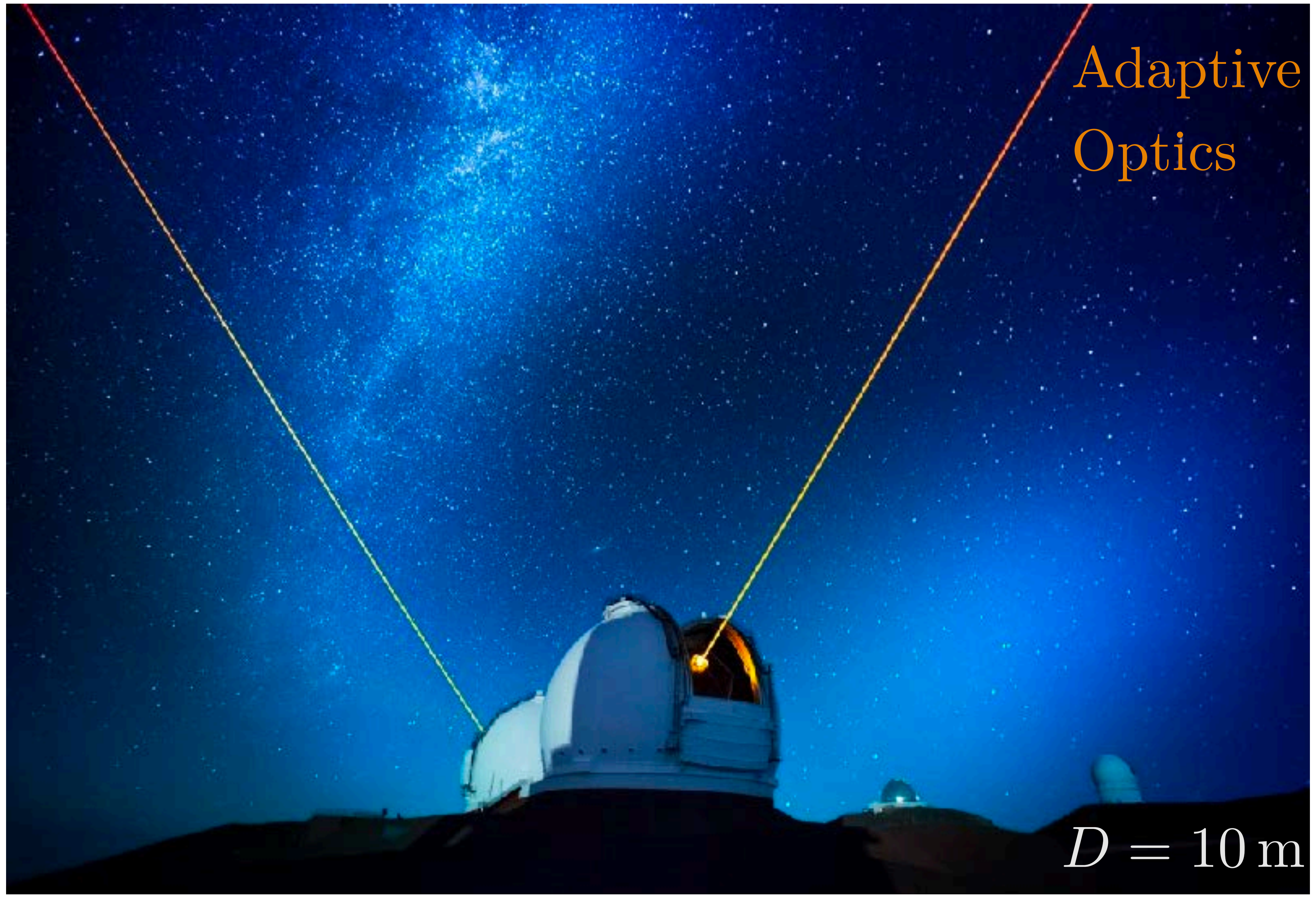
[Book of Fixed Stars]

Abd al-Rahman al-Sufi (903—986)



Tycho Brahe (1546—1601)

Ground-Based Imaging Telescopes

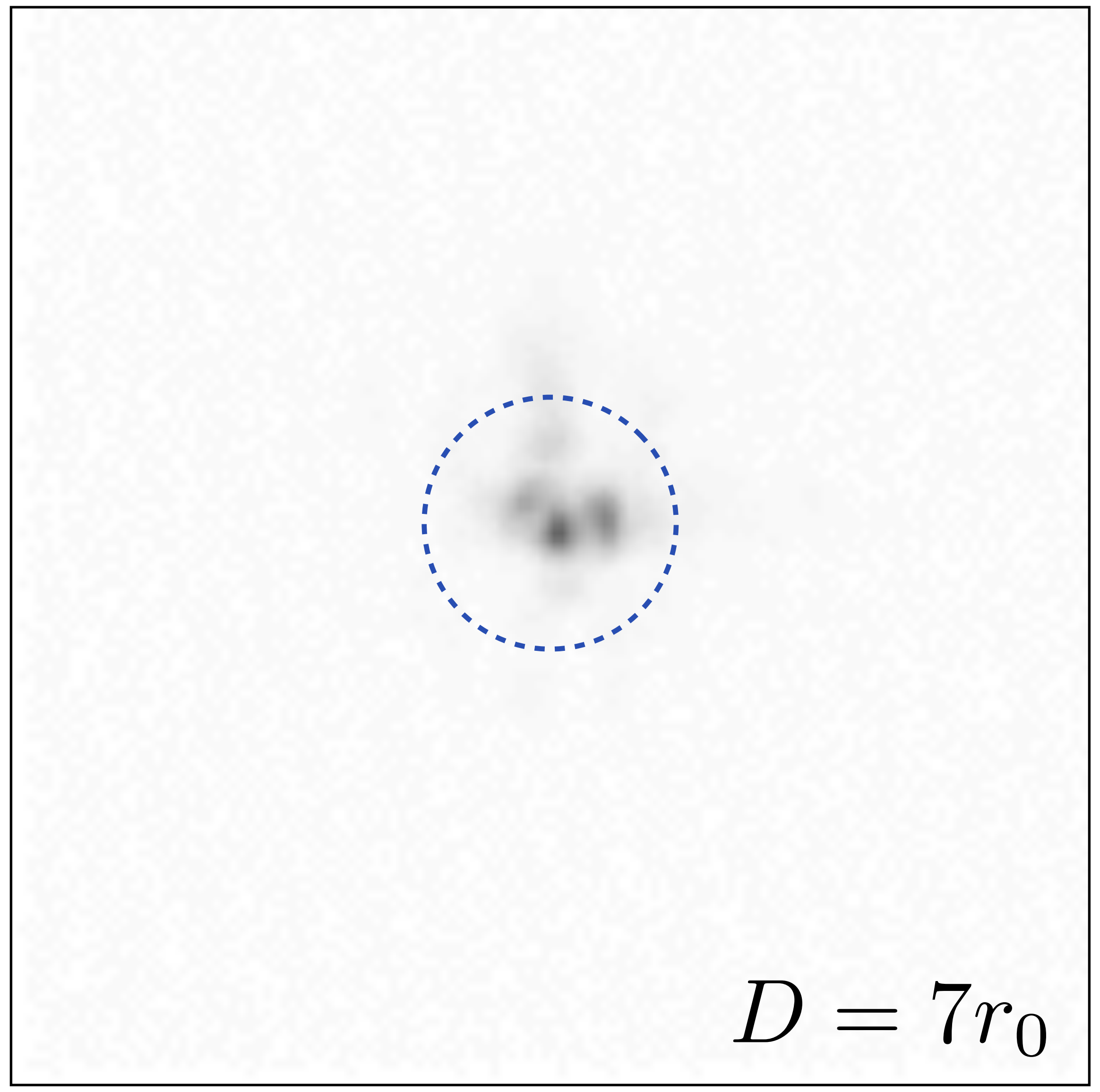


Keck Observatory

$$\sigma_{\theta_{\mathrm{res}}} \sim \frac{\lambda}{\min\{D, r_0\}}$$

Astronomical Seeing

$$r_0 \lesssim 30\,\mathrm{cm} \Rightarrow \sigma_{\theta_{\mathrm{res}}} \gtrsim 0.4\,\mathrm{arcsec}$$



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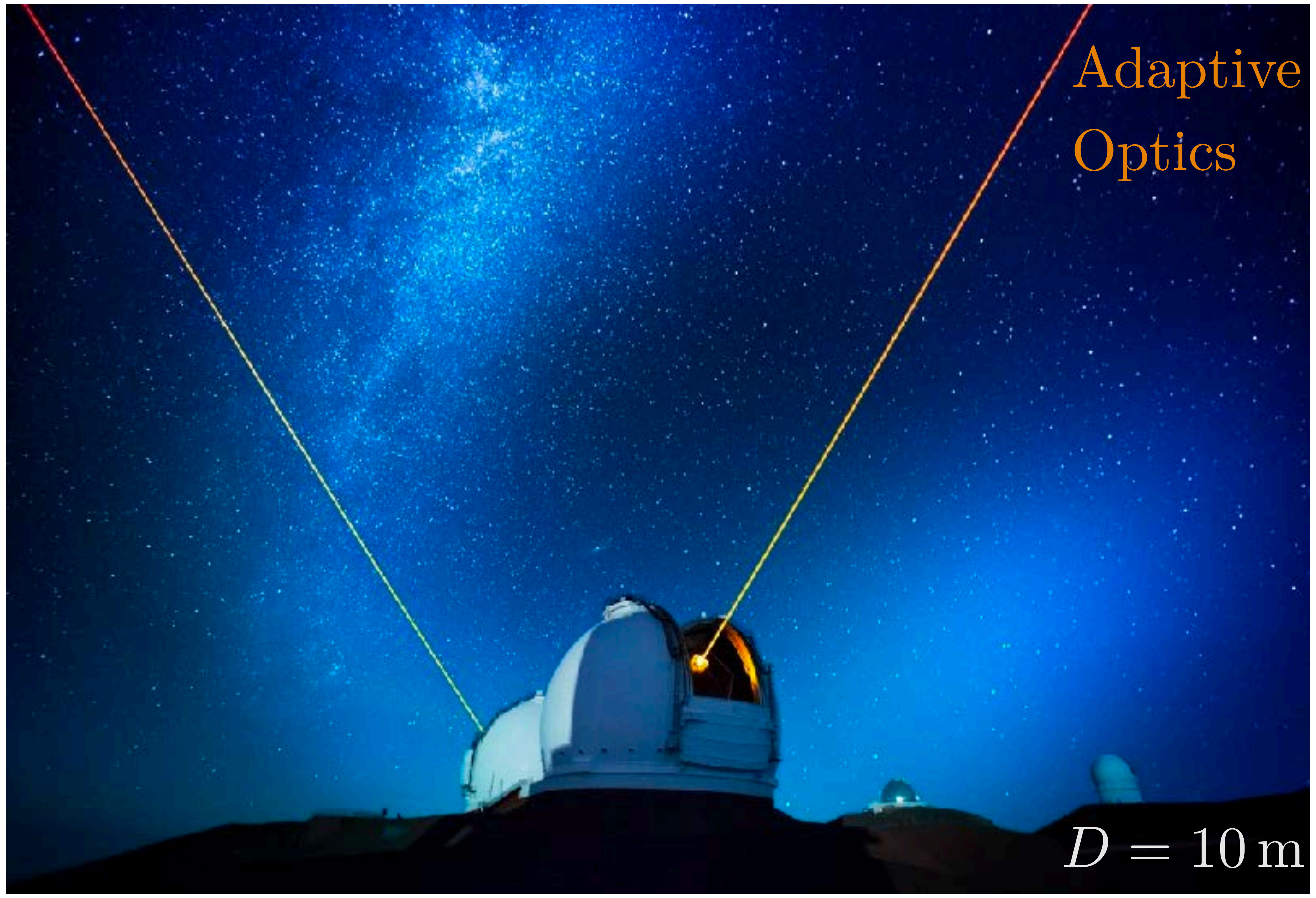

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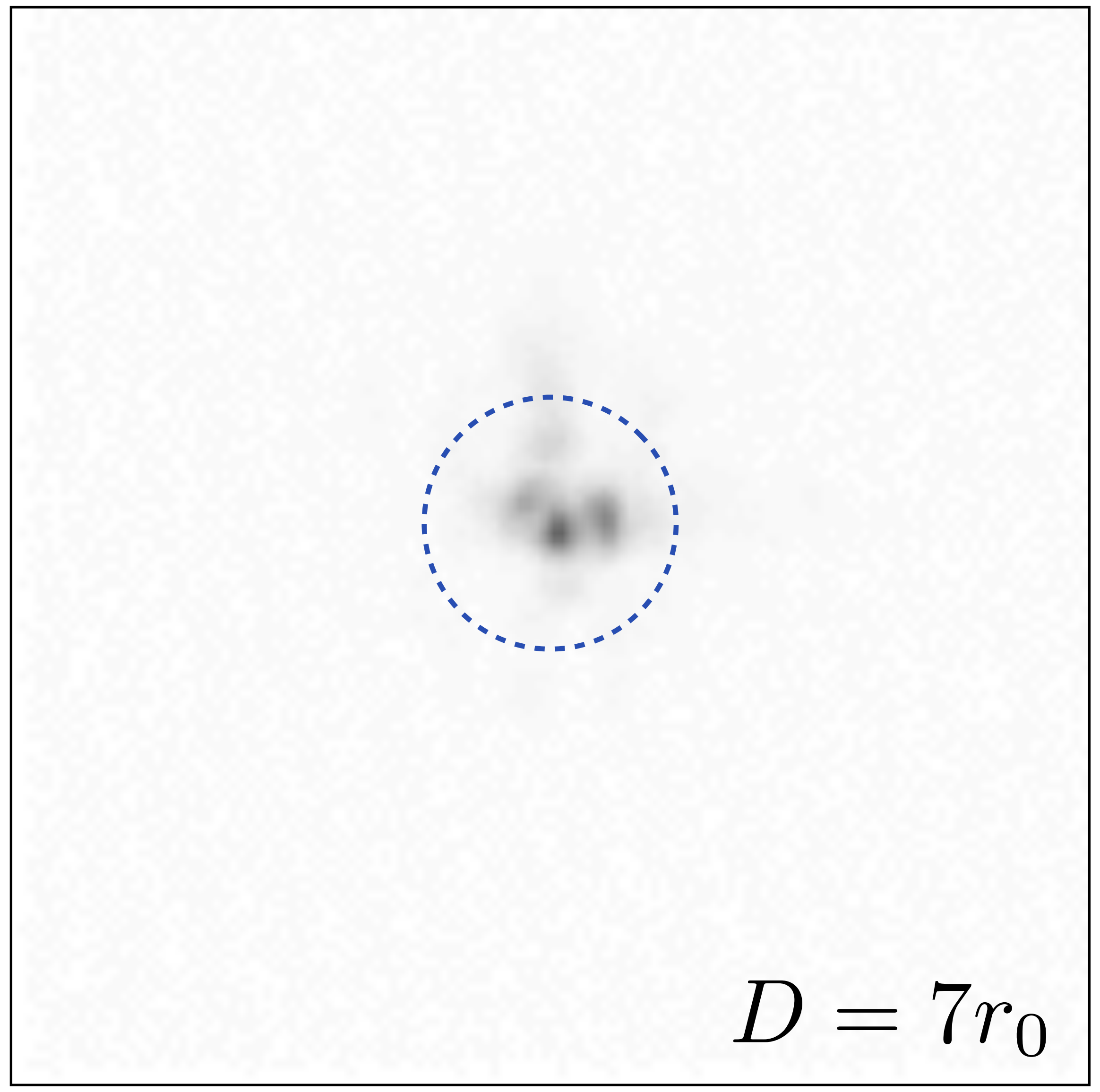
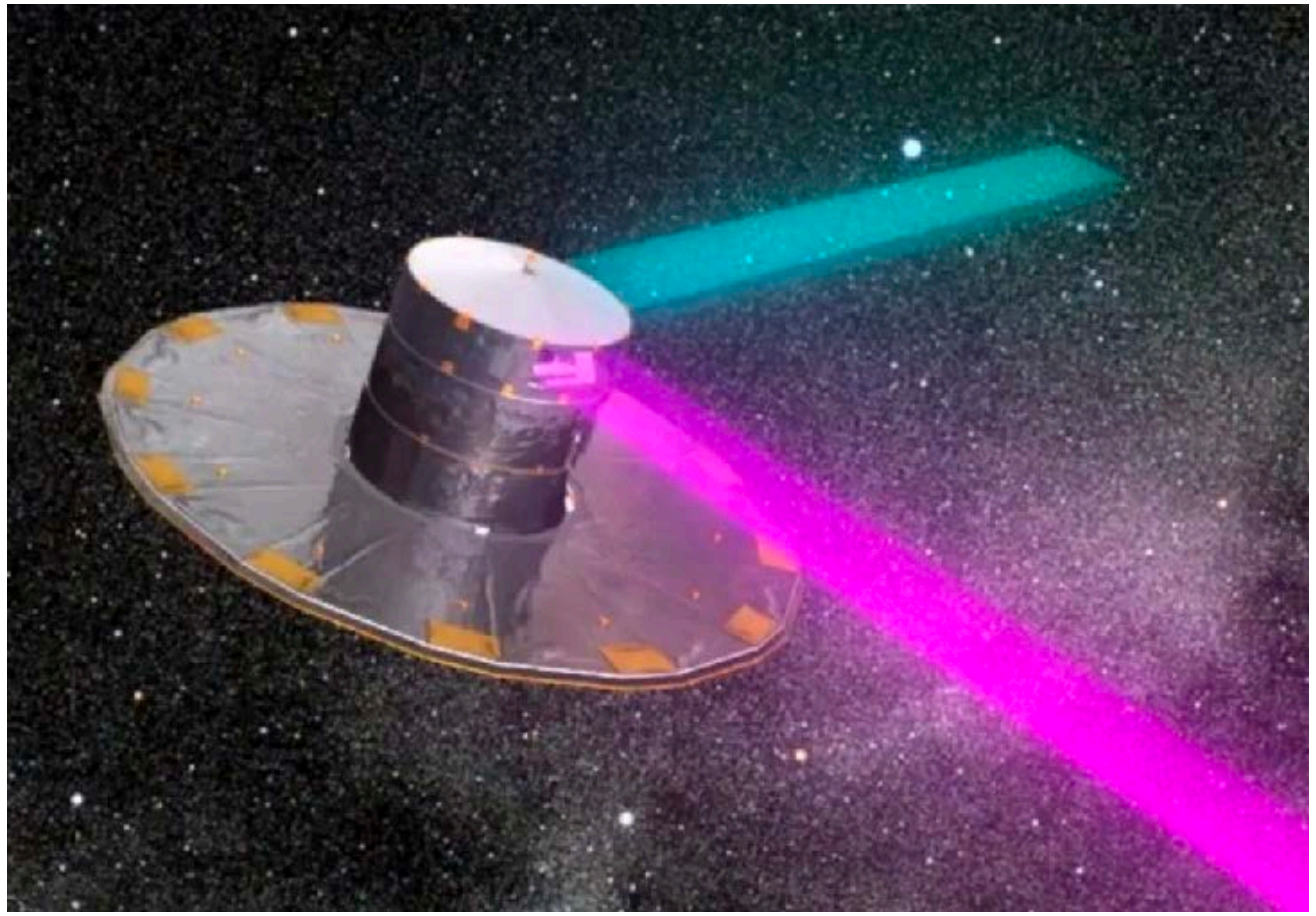


Space-Based Imaging Telescopes

$N_{\text{stars}} \sim 118{,}200$

$\sigma_{\delta\theta} \sim 10\,\text{mas}$

Hipparcos (1989–1993)



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

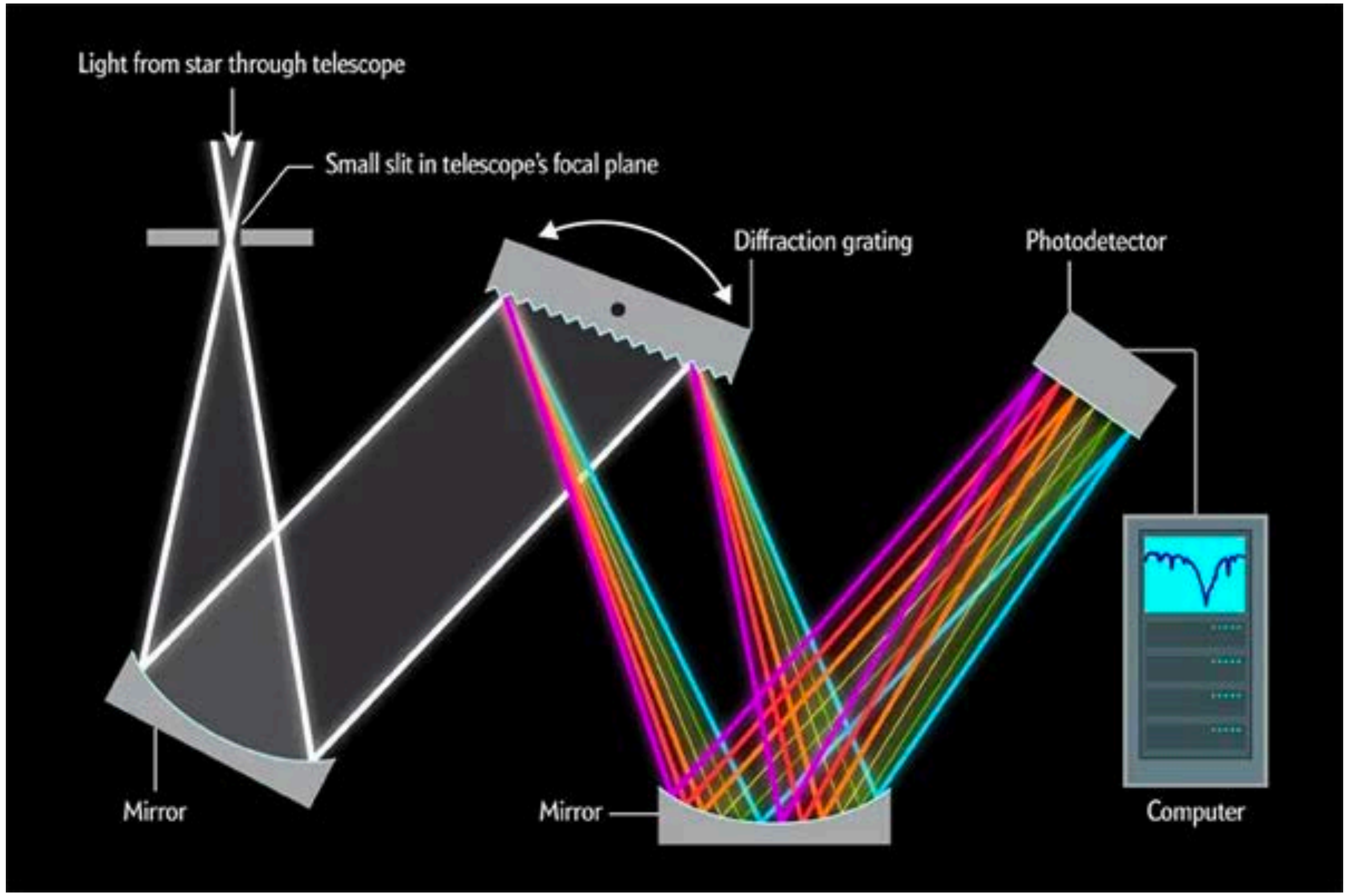
$\sigma_{\delta\theta} \sim 100\,\mu\text{as}$

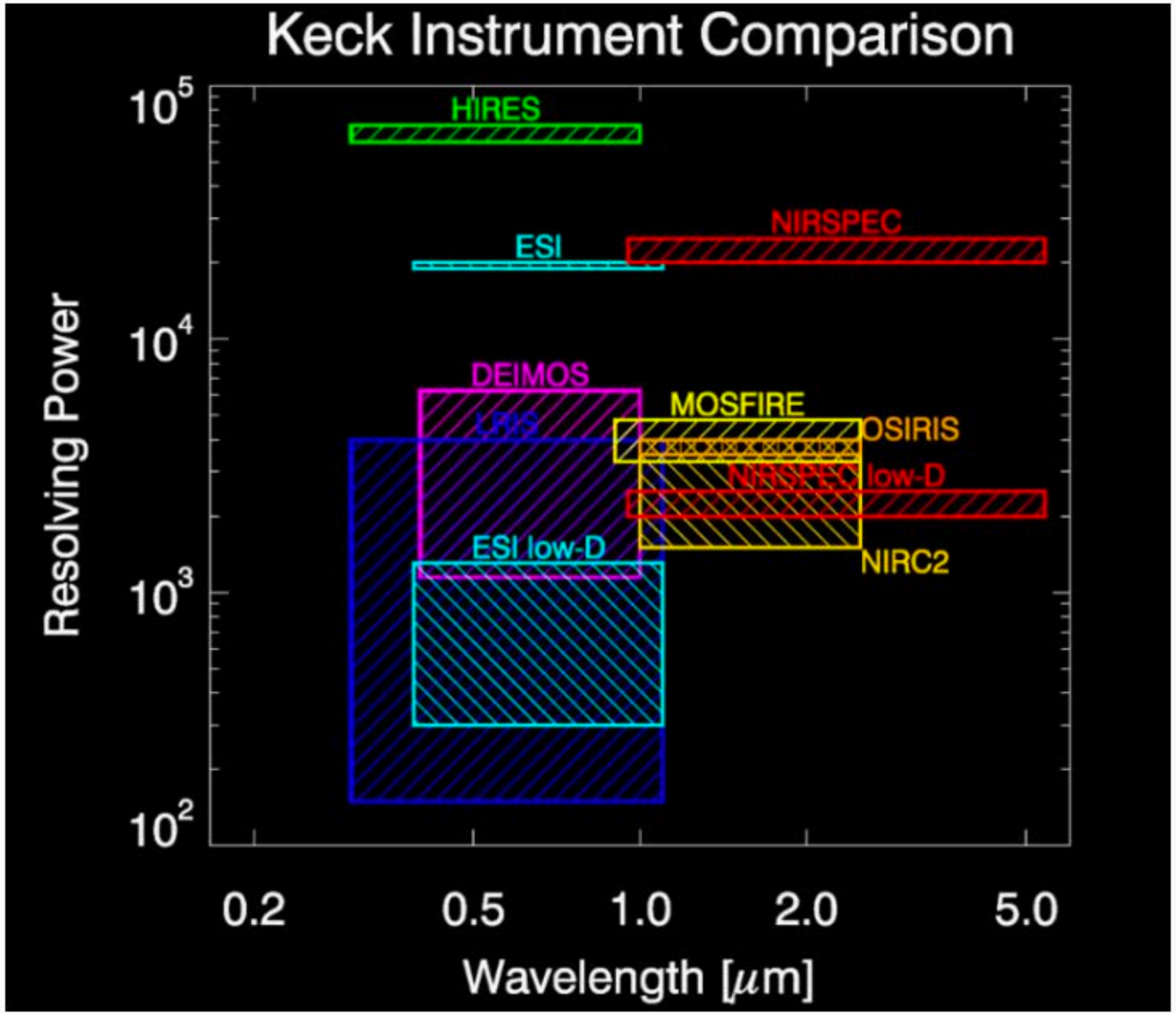
Gaia (2014–2024)

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

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

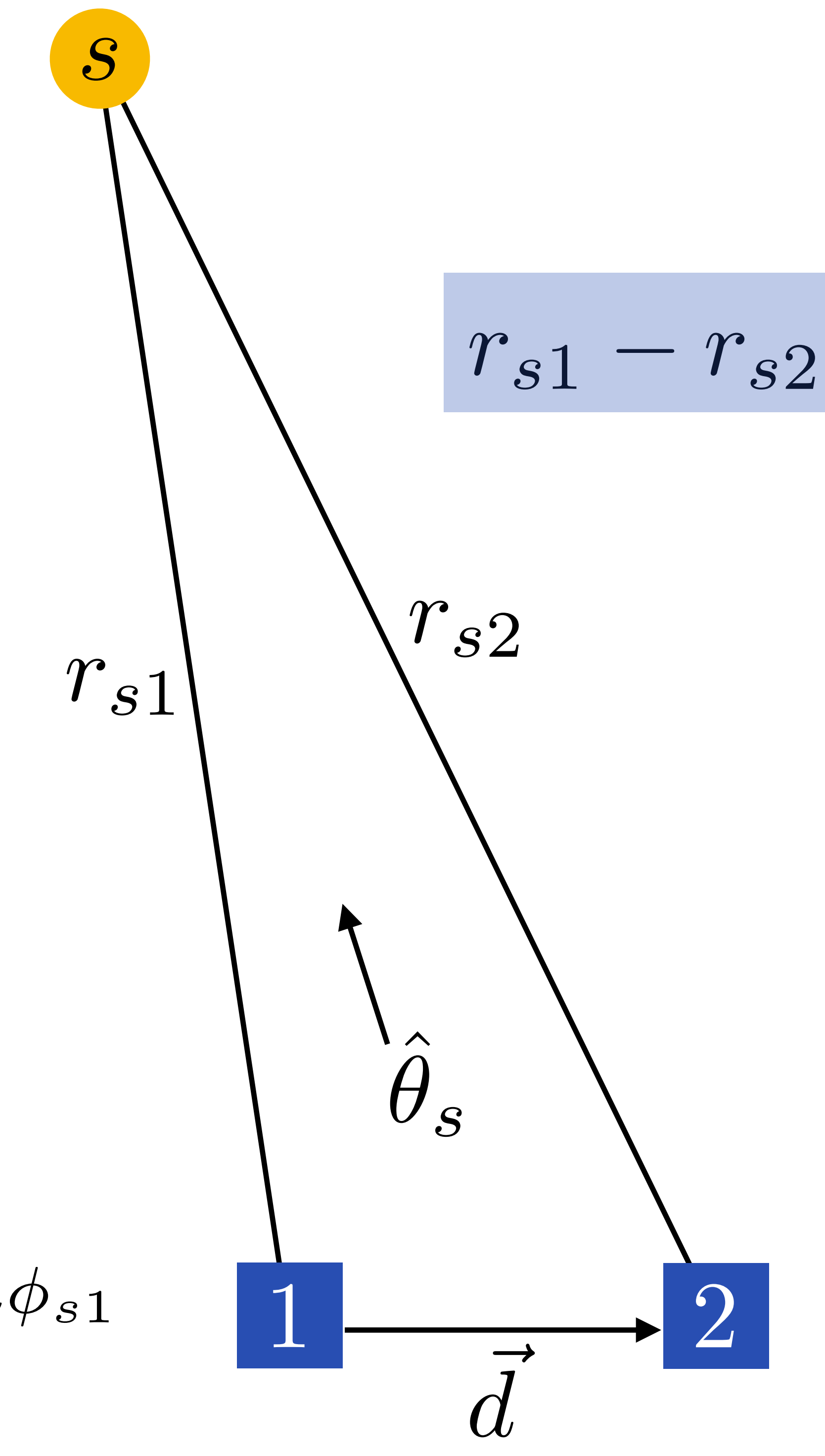
Spectrographs





Keck Observatory

Amplitude Interferometers



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

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

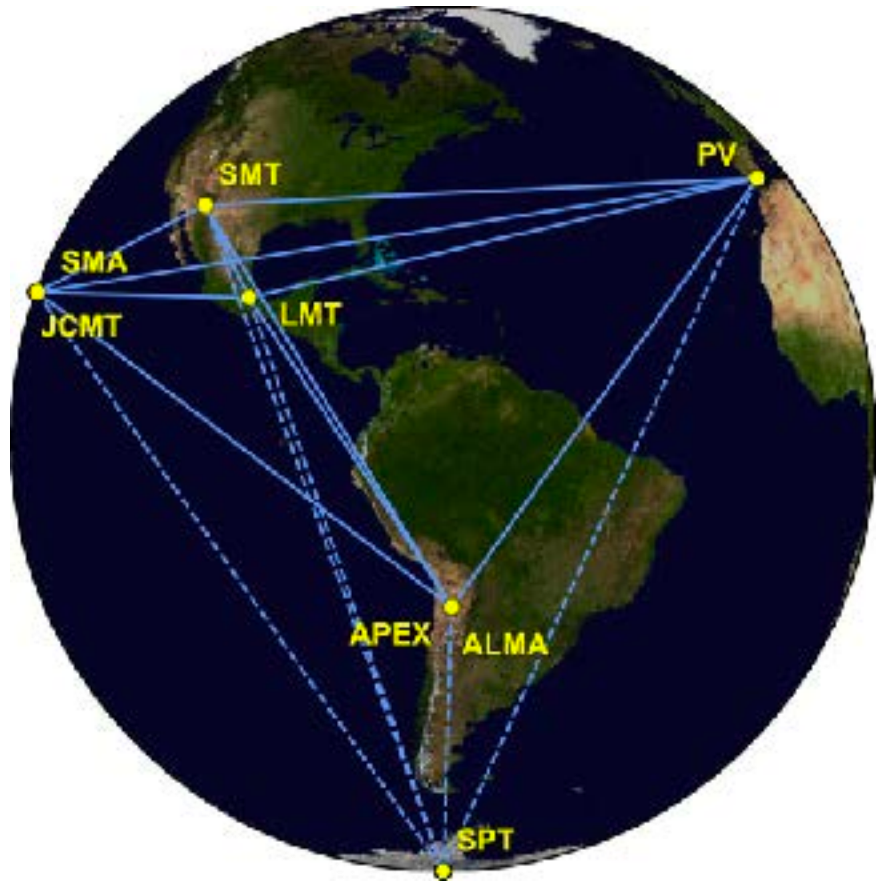
$$\phi_{sj}(t) = -\omega t + k r_{sj} + \phi_s^{\rm em}(t - r_{sj})$$

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

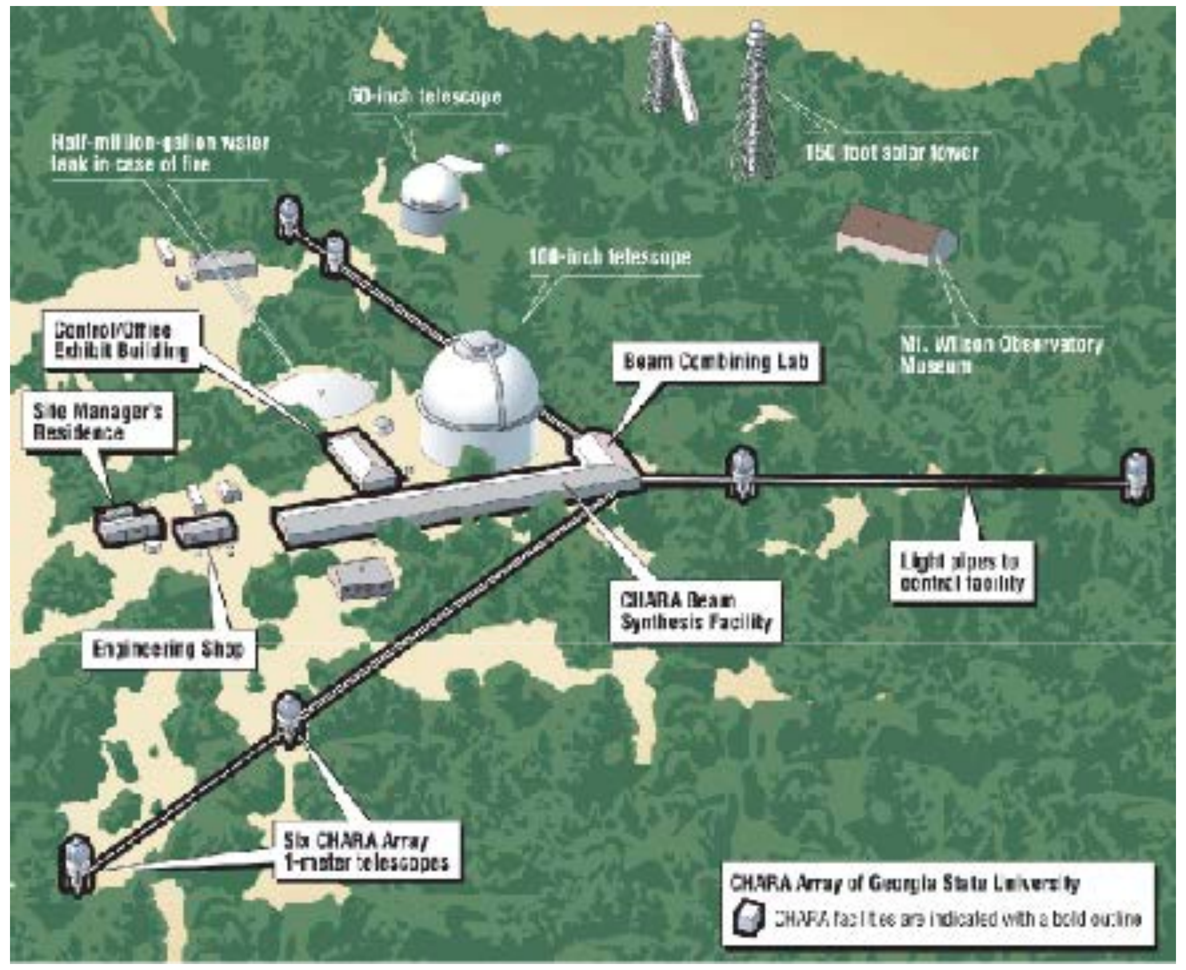
$$\sigma_{\delta\theta} \simeq \frac{1}{\rm SNR}\sigma_{\theta_{\rm res}}$$

$$\langle E_1(t) E_2^*(t+\tau)\rangle = E_s^2 e^{ik(r_{s1}-r_{s2})}\left\langle e^{i[\phi_s^{\rm em}(t-r_{s1})-\phi_s^{\rm em}(t+\tau-r_{s2})]}\right\rangle$$

$$= E_s^2 e^{ik(r_{s1}-r_{s2})} e^{-\frac{\sigma_k^2}{2}(\tau + r_{s1} - r_{s2})^2}$$



Event Horizon Telescope
$\sigma_{\theta_{\rm res}} \approx 30\,\mu$as



CHARA Array
$\sigma_{\theta_{\rm res}} \approx 200\,\mu$as

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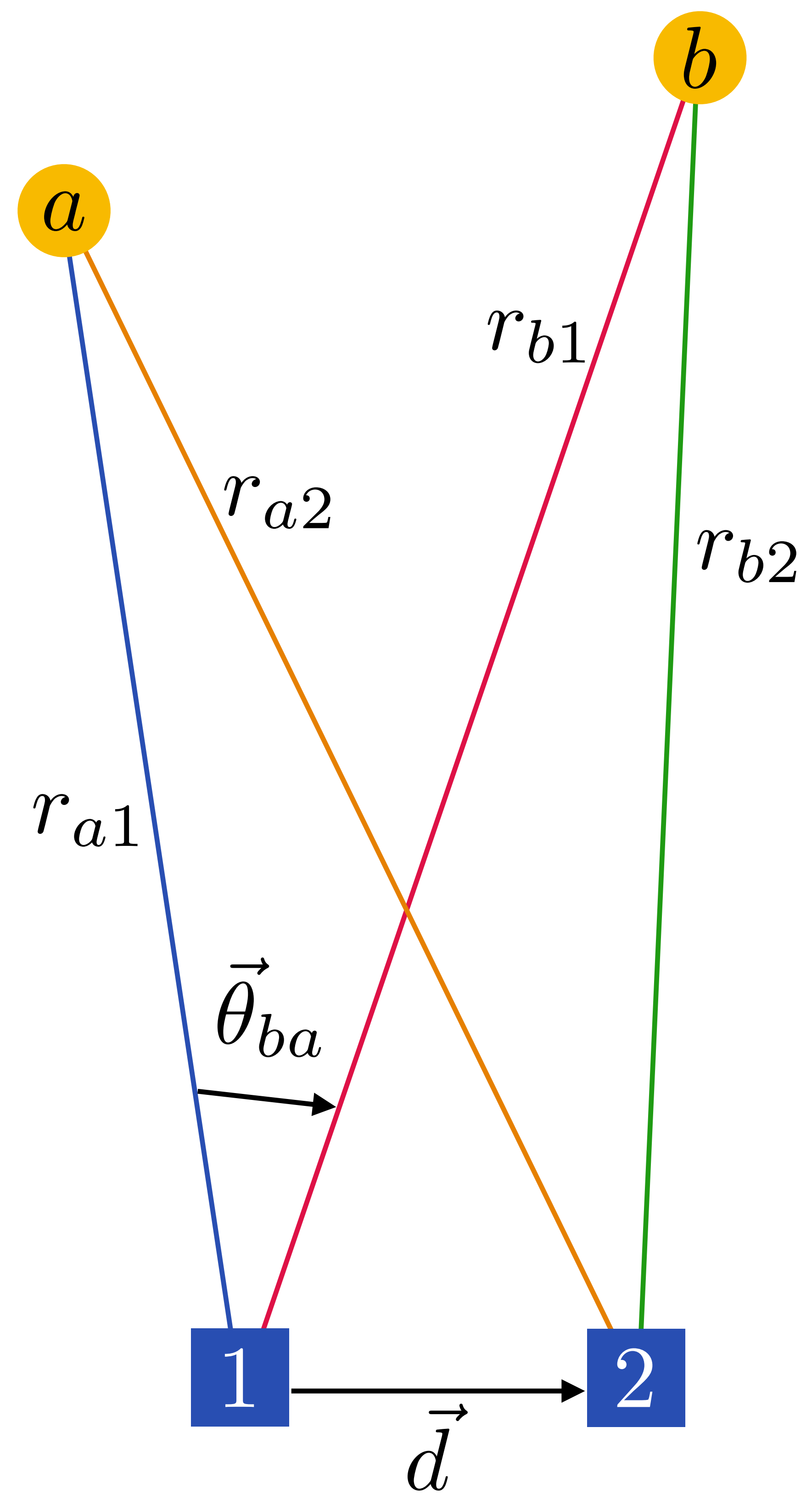
Intensity Interferometry

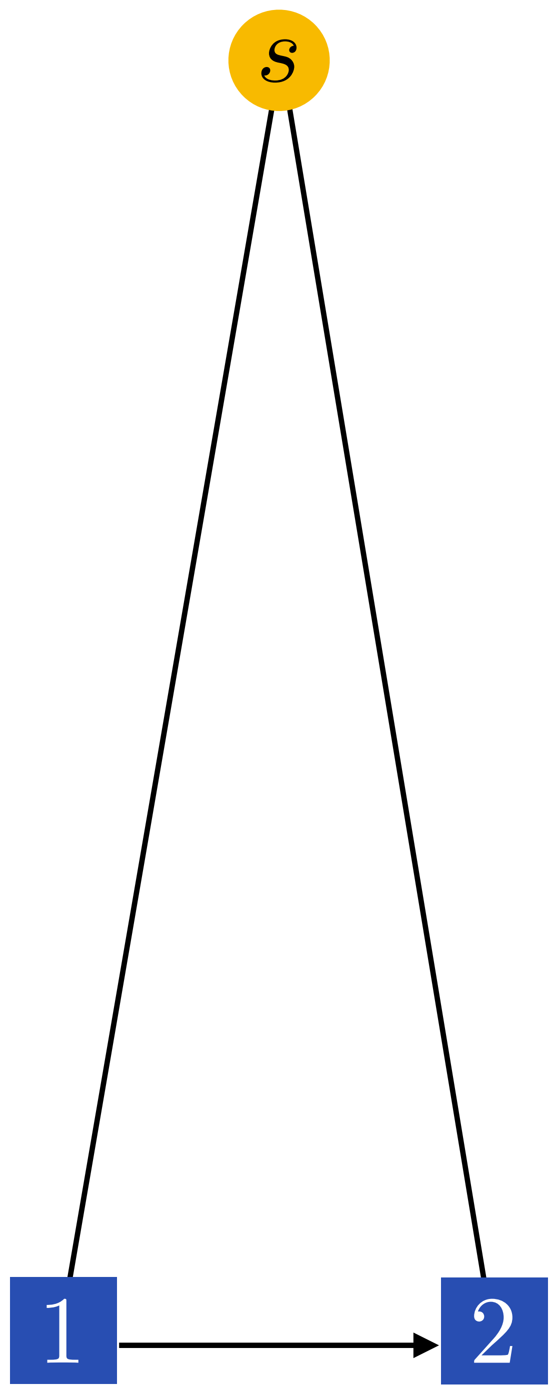
sub-μas resolution and even better *differential* light-centroiding precision

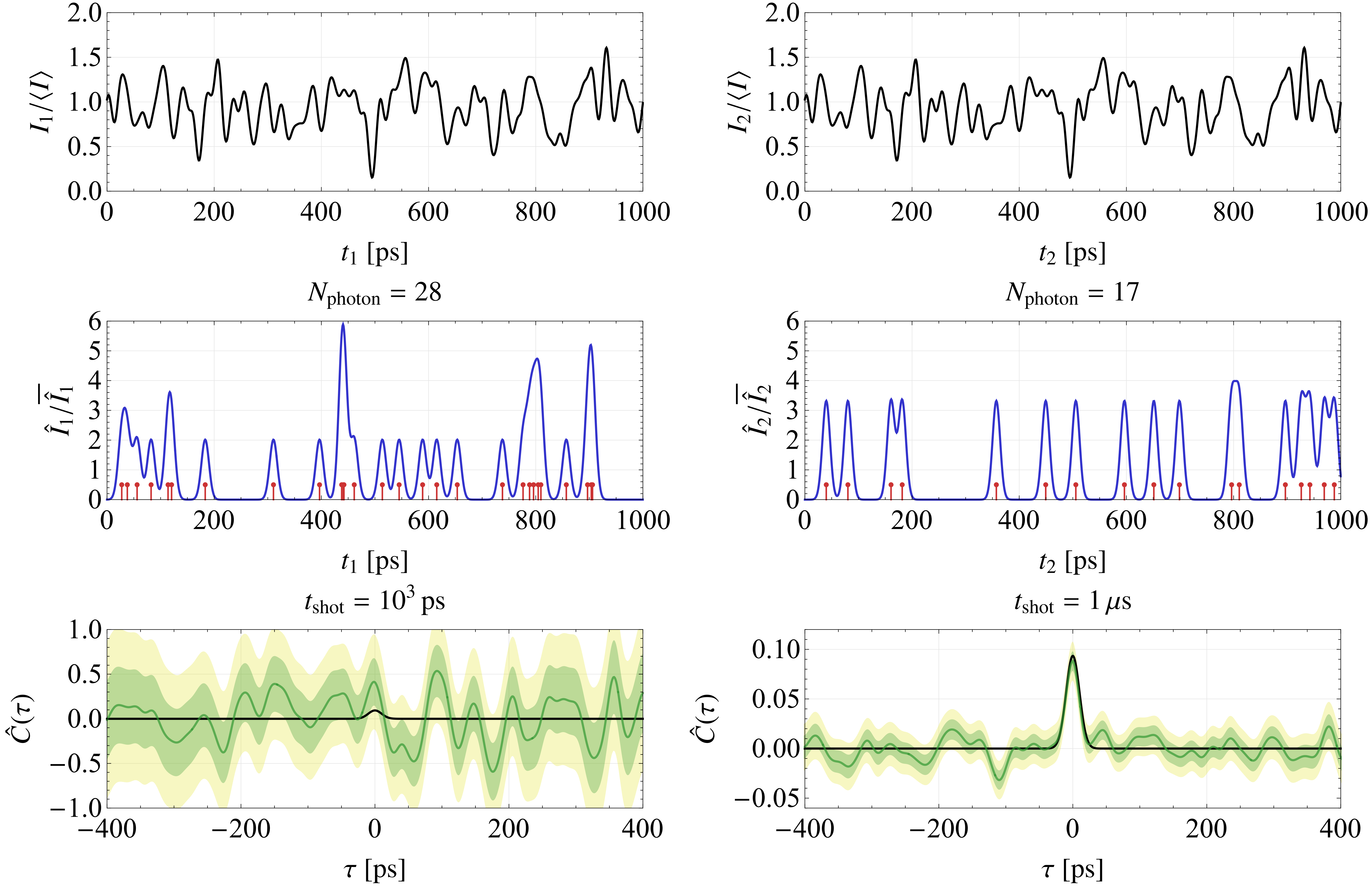


Intensity Correlations

One Source

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



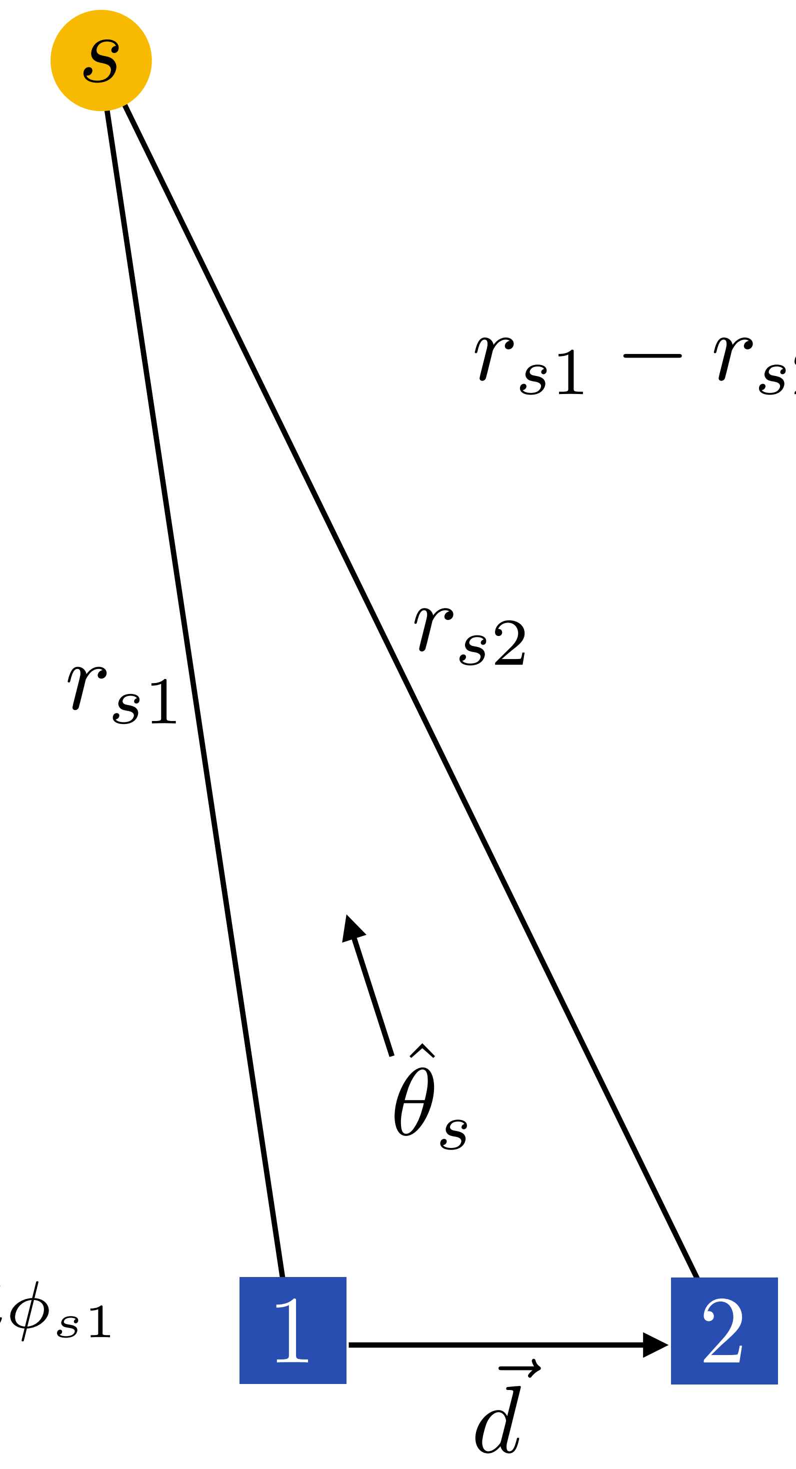


$$C(\tau) = \frac{\langle I_1(t) I_2(t+\tau) \rangle}{\langle I_1 \rangle \langle I_2 \rangle} - 1$$

Intensity Correlations

One Source

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



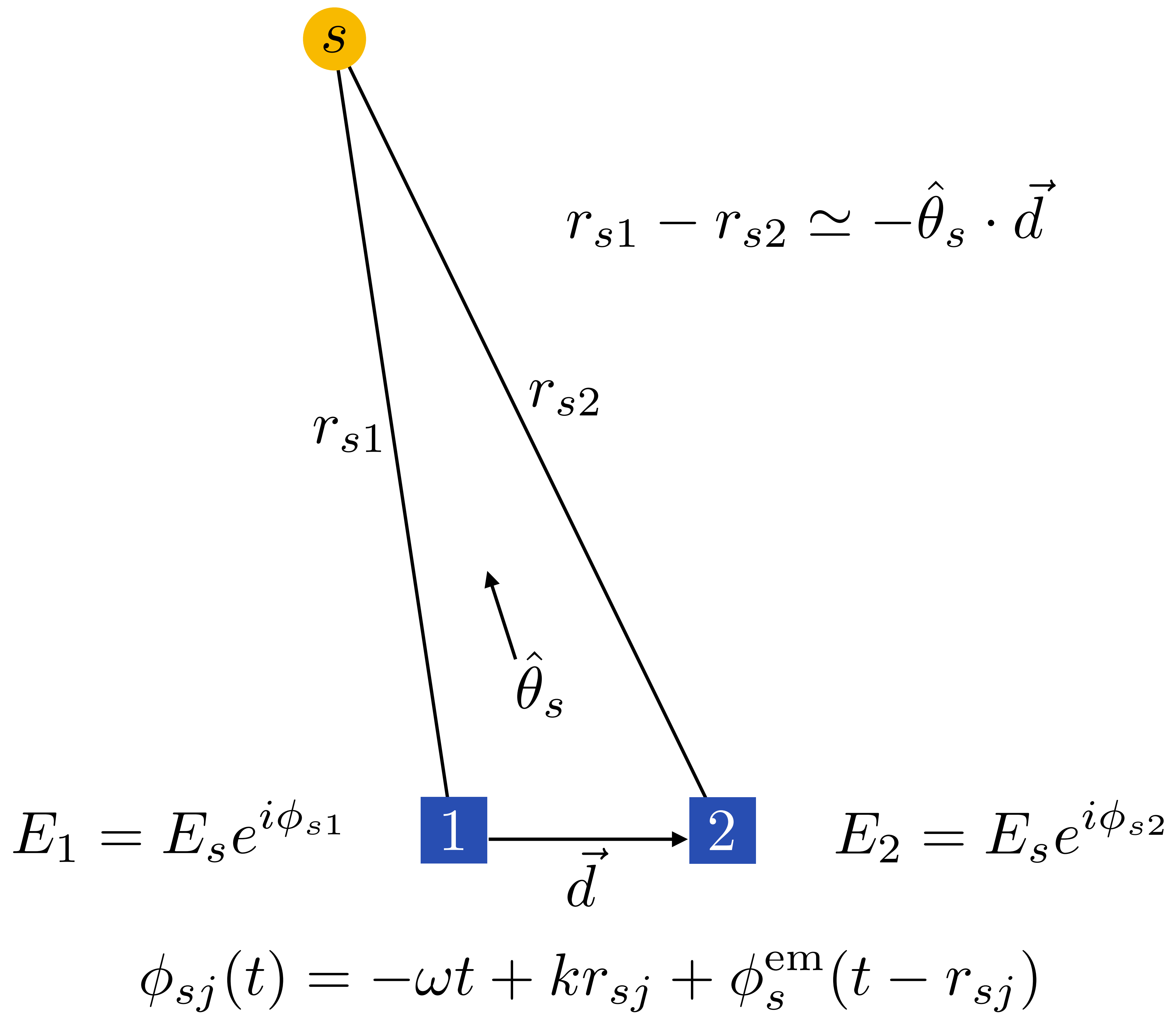
$$E_1 = E_s e^{i\phi_{s1}} \qquad E_2 = E_s e^{i\phi_{s2}}$$

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

$$\begin{aligned} C &\equiv \frac{\langle I_1(t) I_2(t+\tau)\rangle}{\langle I_1\rangle \langle I_2\rangle} - 1 \\ &= \frac{\langle E_1(t)E_1^*(t)E_2(t+\tau)E_2^*(t+\tau)\rangle}{\langle E_1 E_1^*\rangle \langle E_2 E_2^*\rangle} - 1 \end{aligned}$$

Intensity Correlations

One Source



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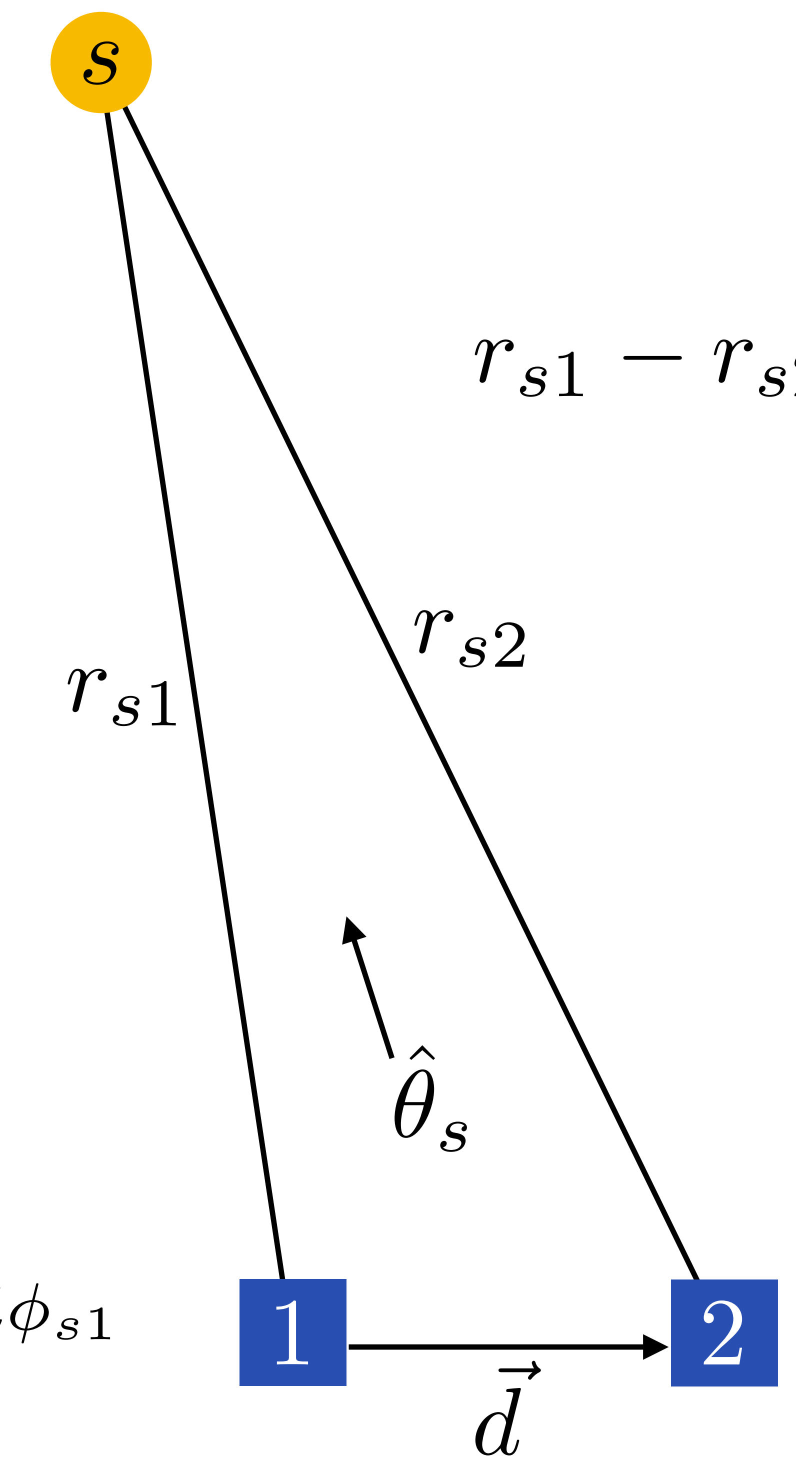

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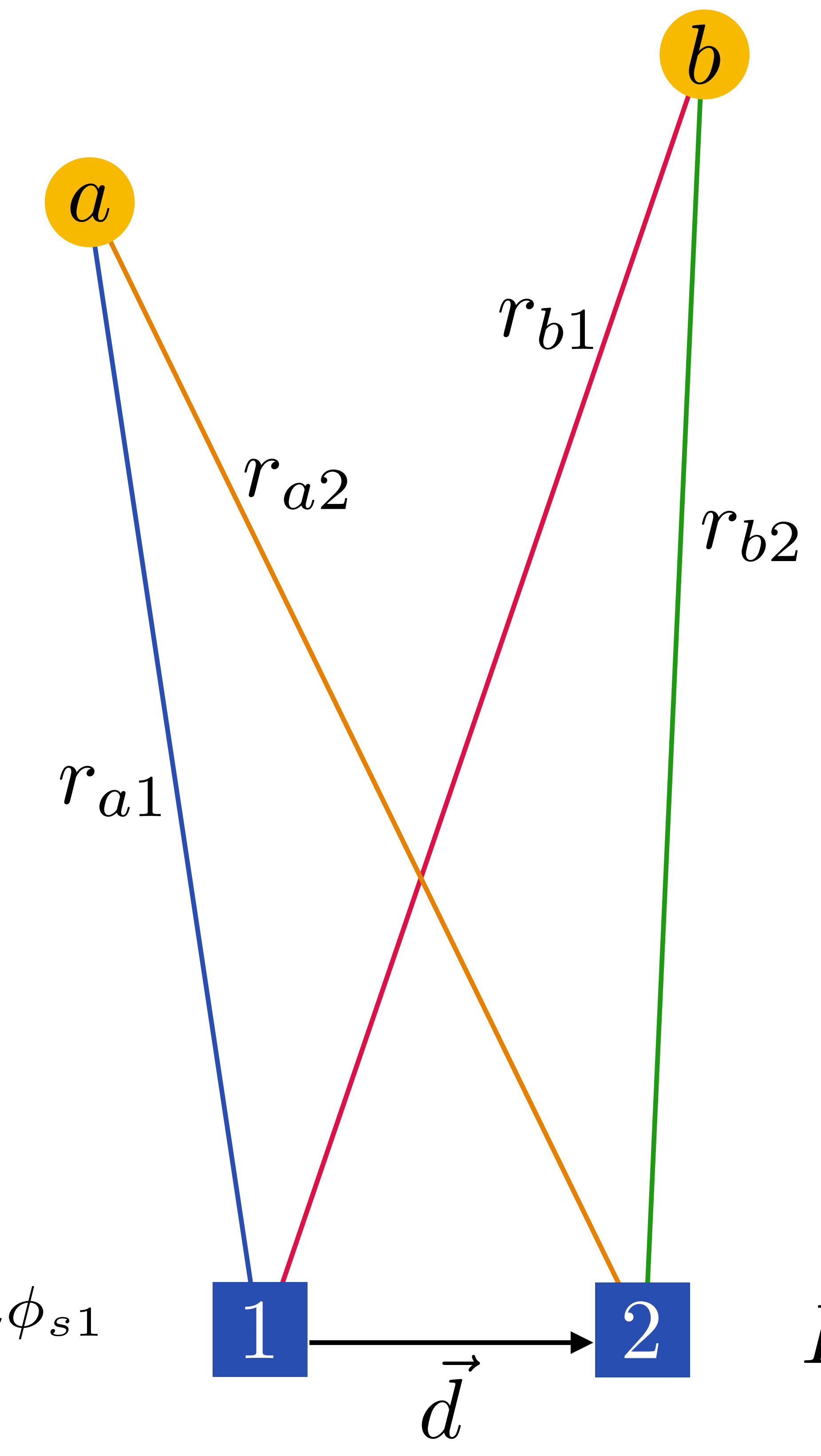
$$\sigma_{\hat{\theta}} \sim \frac{1}{\mathrm{SNR}} \frac{\sigma_t}{d} \sim \frac{10\,\mathrm{mas}}{\mathrm{SNR}} \left(\frac{\sigma_t}{10\,\mathrm{ps}}\right) \left(\frac{100\,\mathrm{km}}{d}\right)$$

Intensity Correlations

Two Sources



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

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

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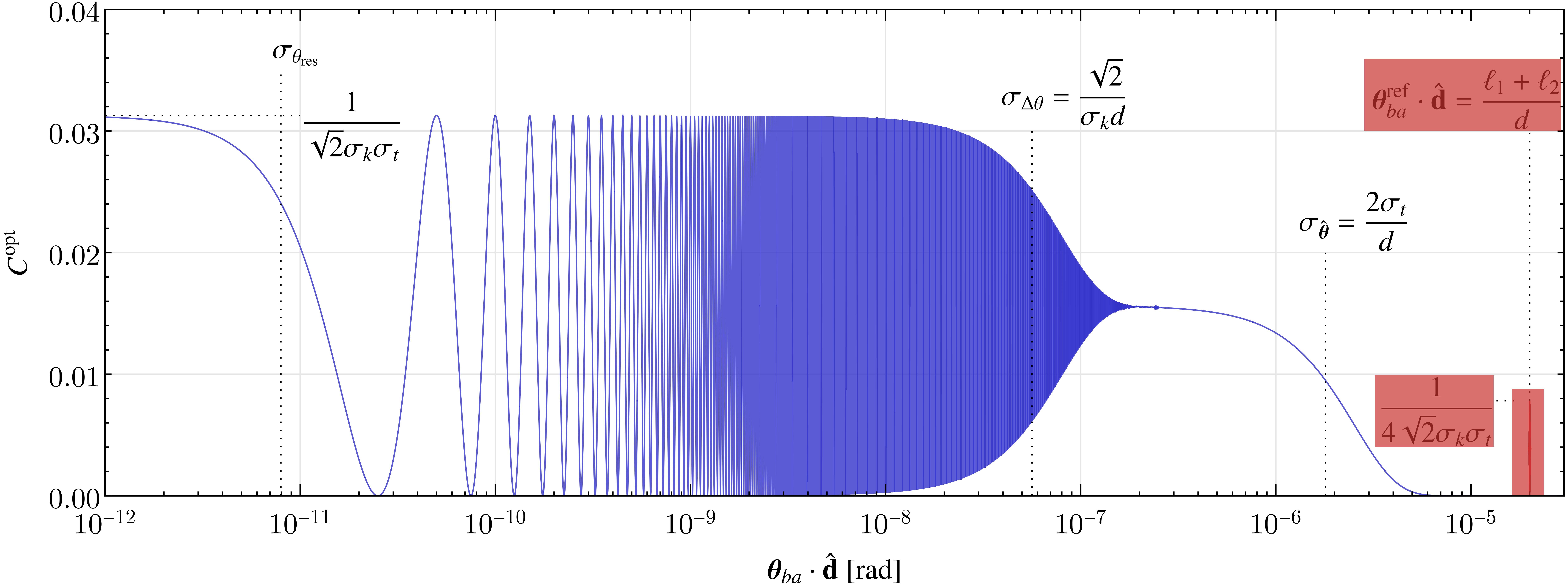
Two Sources

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

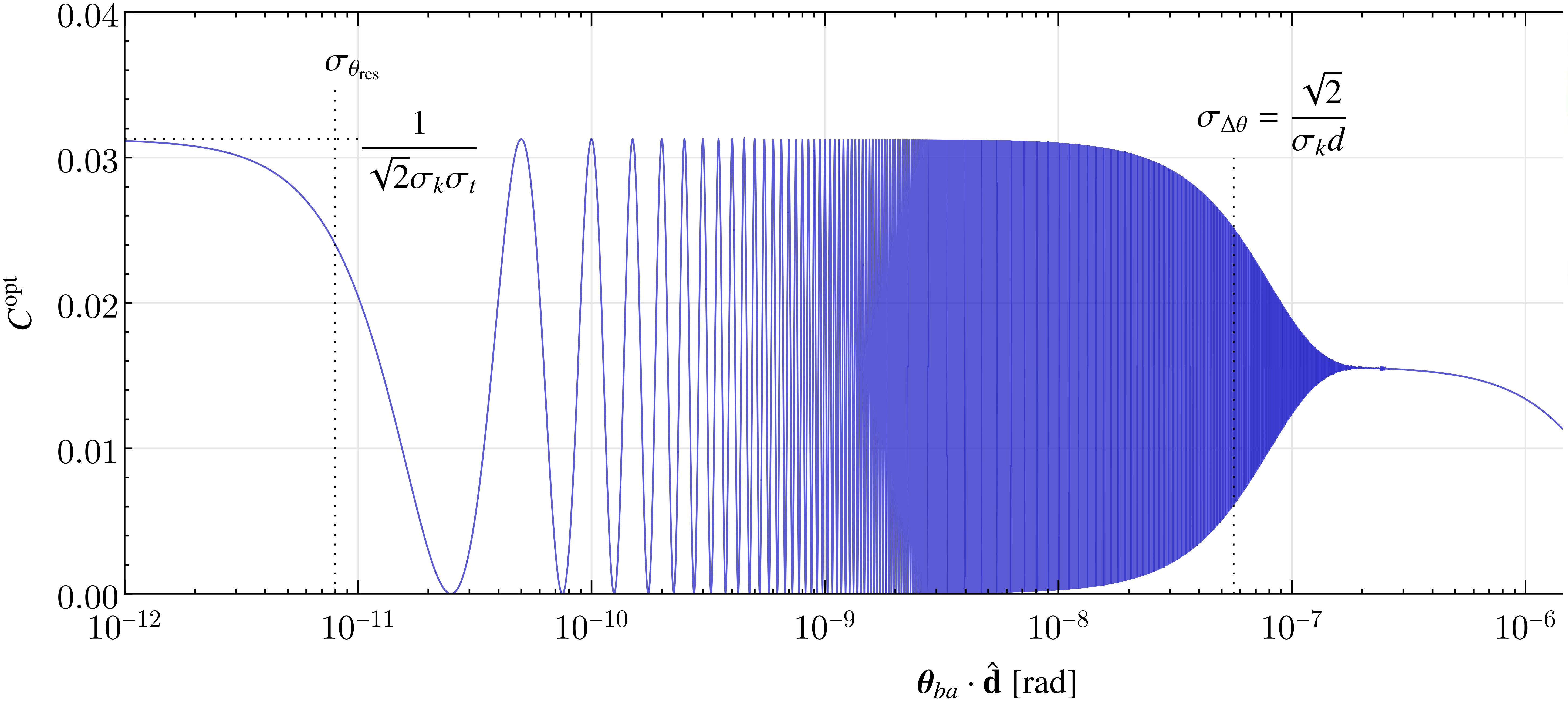


Limitations

Field of View

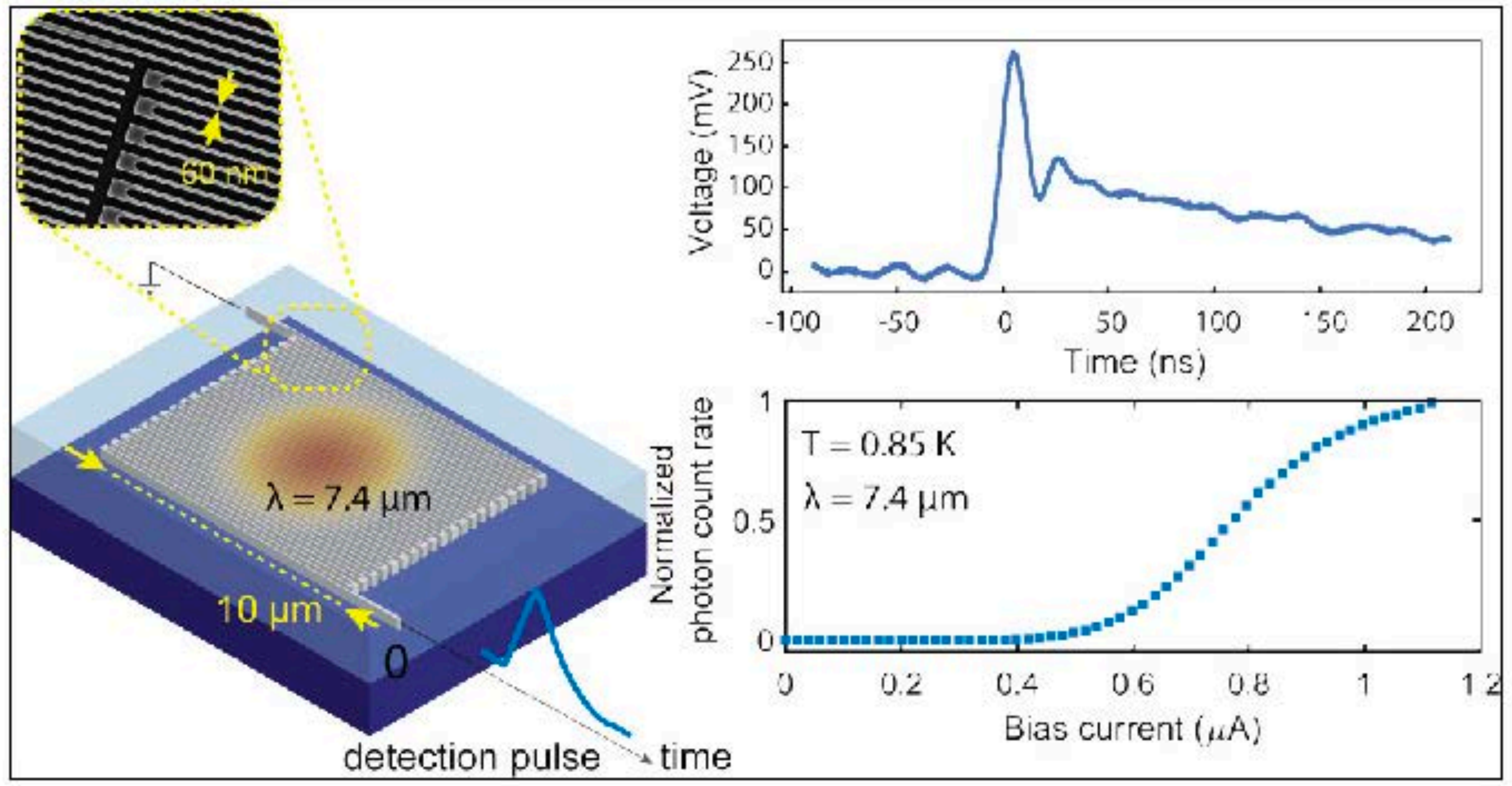
$$\sigma_{\Delta\theta} \sim \underbrace{\mathcal{R}}_{k/\sigma_k} \sigma_{\theta_{\rm res}} \sim \underbrace{5 \times 10^{-8}\,\mathrm{rad}}_{10\,\mathrm{mas}} \left(\frac{\mathcal{R}}{5{,}000}\right) \left(\frac{\lambda}{500\,\mathrm{nm}}\right) \left(\frac{10\,\mathrm{km}}{d}\right)$$

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

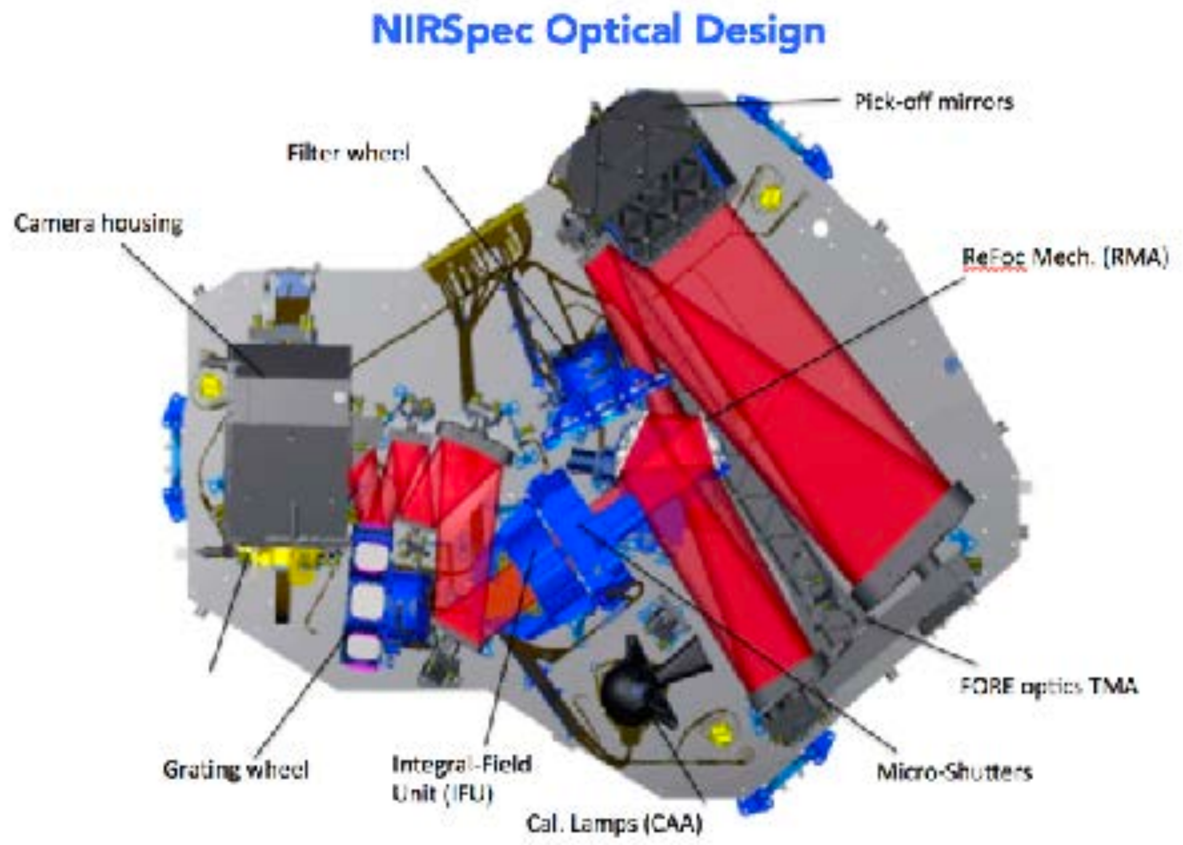


Extended Path

Signal-to-Noise Ratio

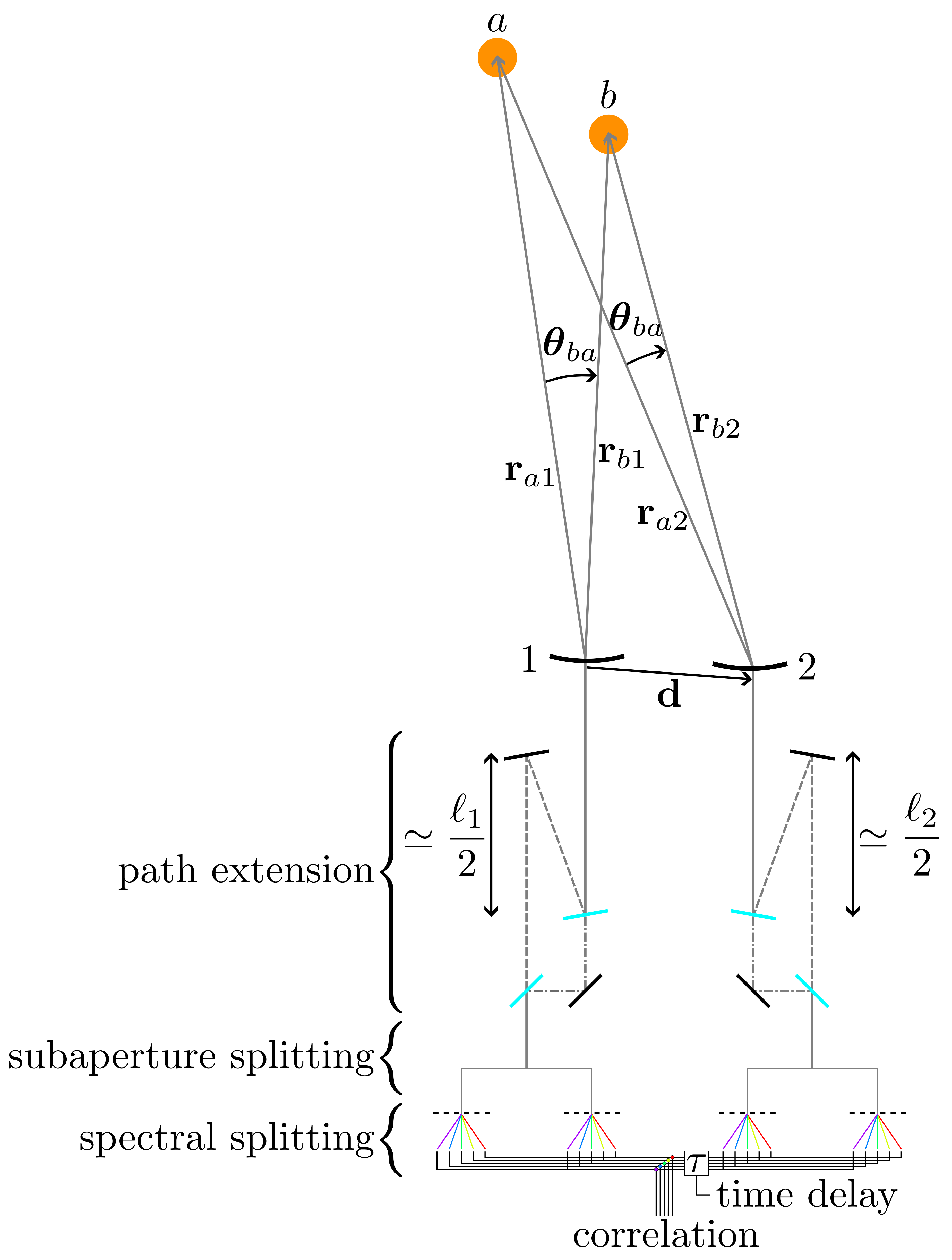


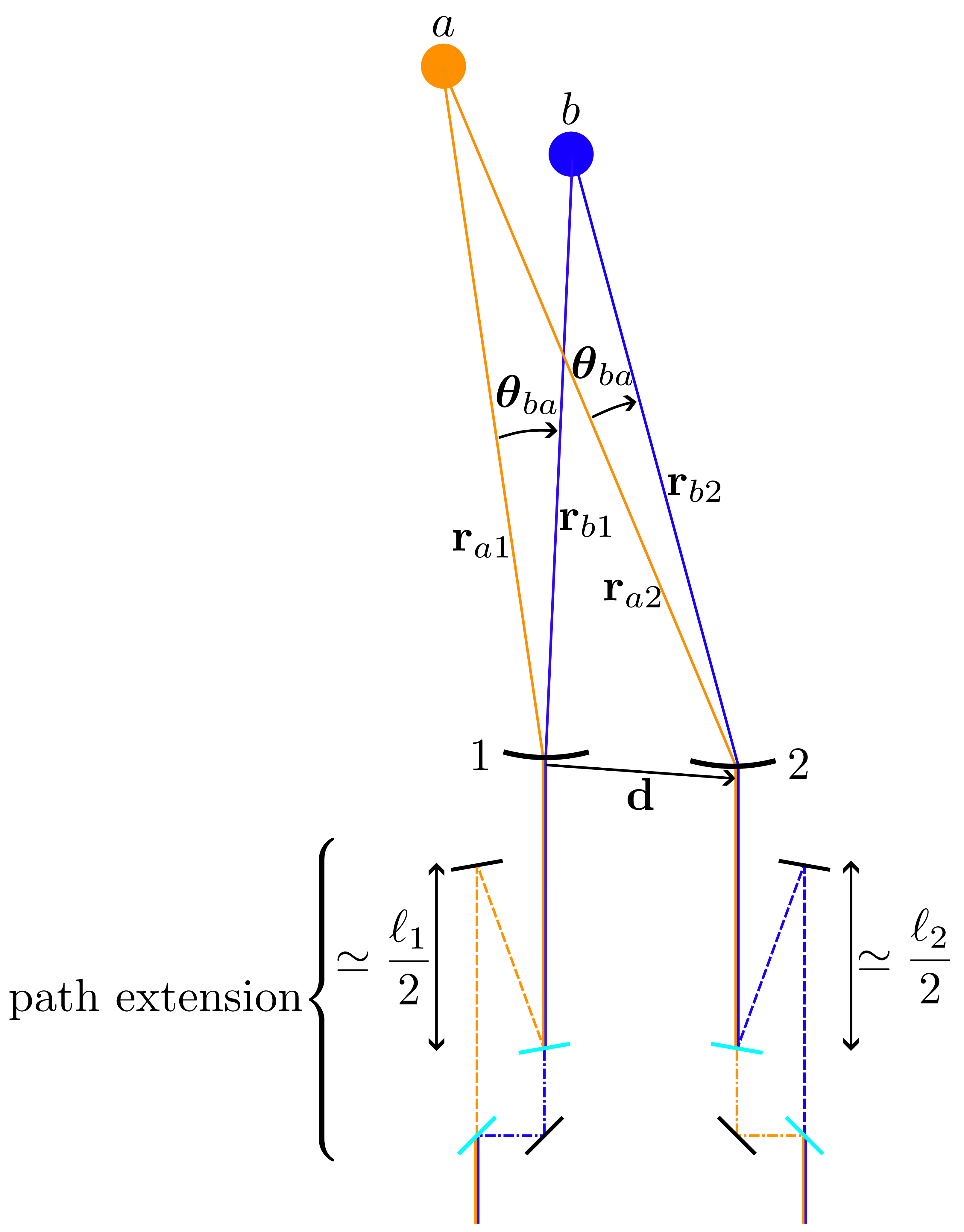
Fast Single-Photon Detection



Multi-Channel Spectroscopy

Extended Path Intensity Correlation





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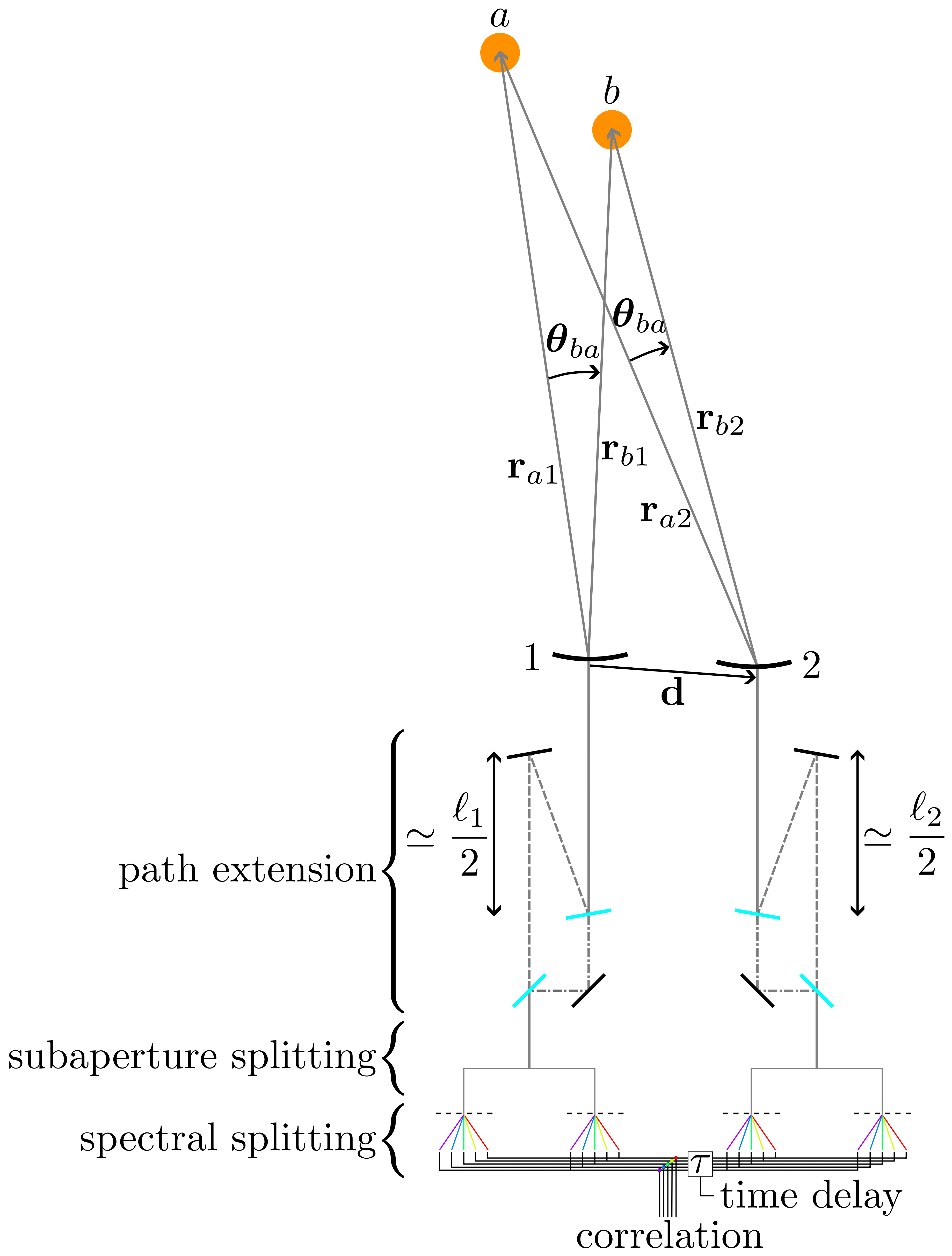
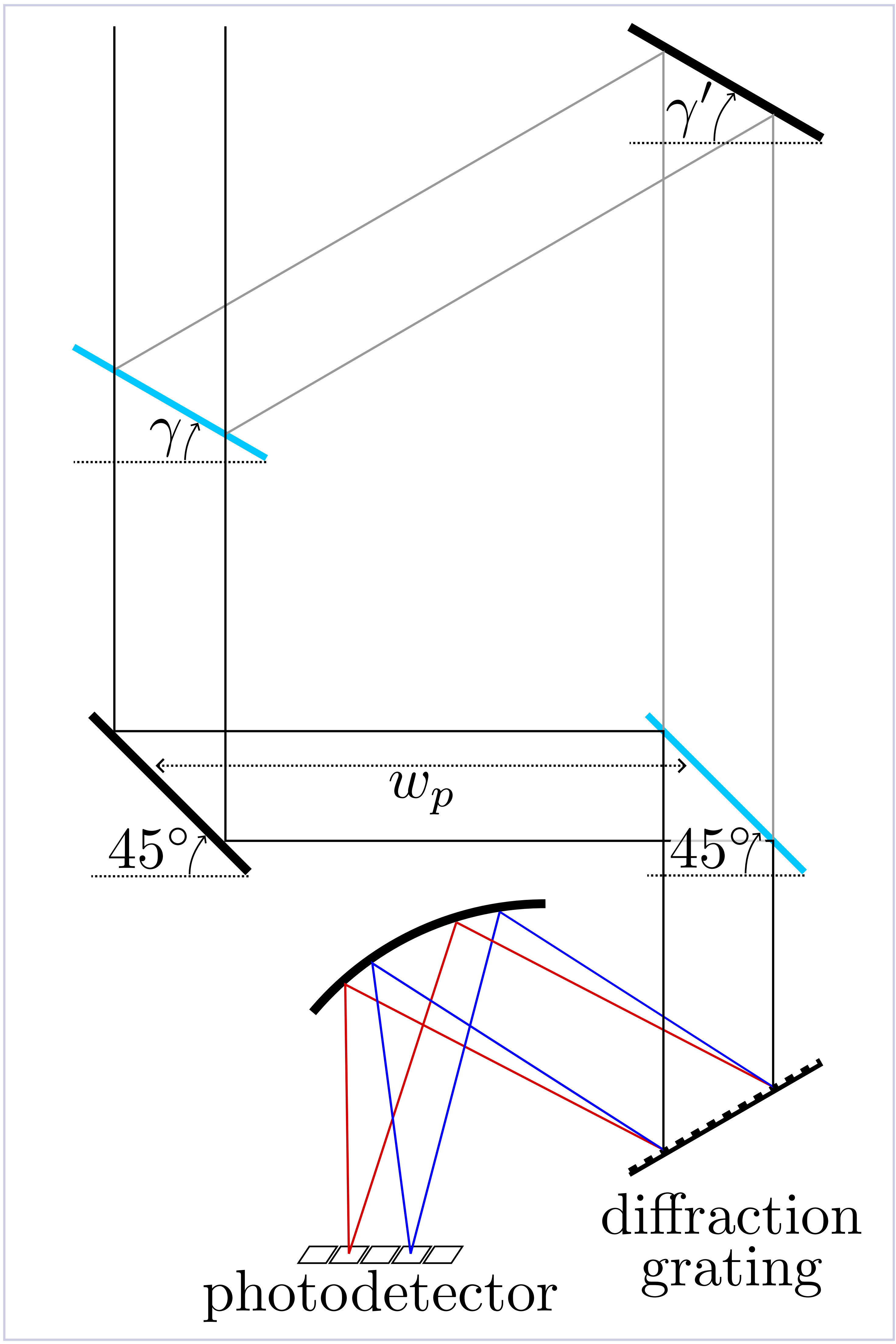
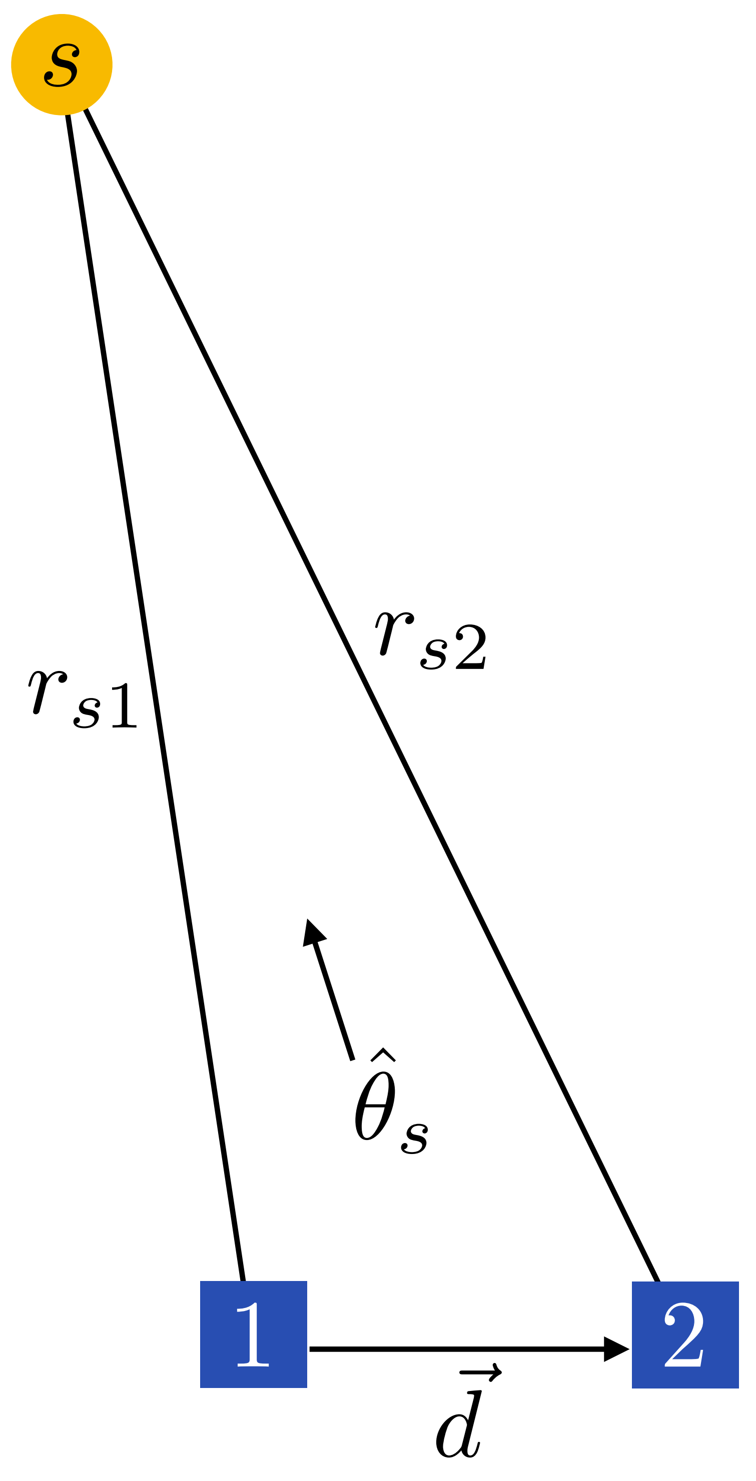
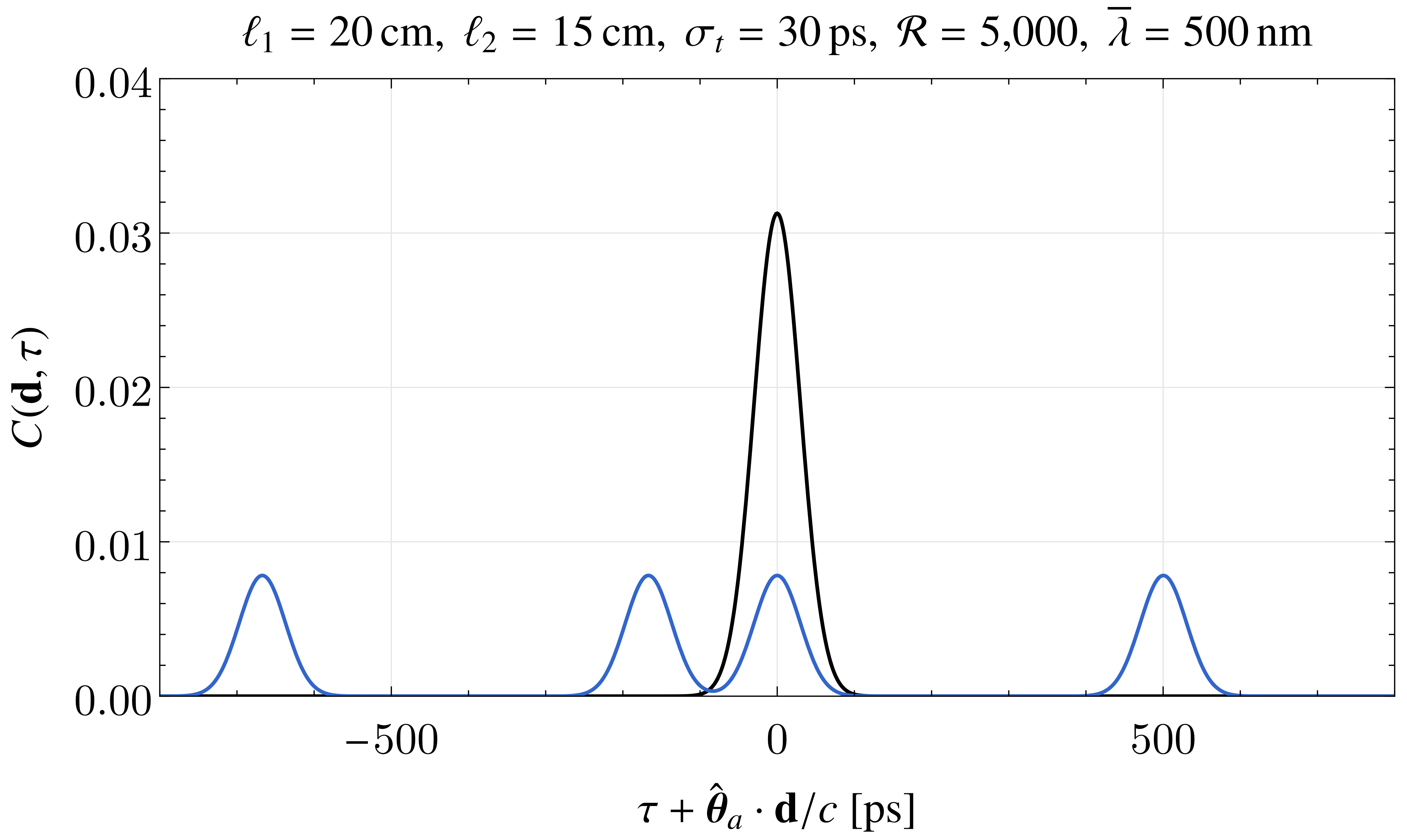


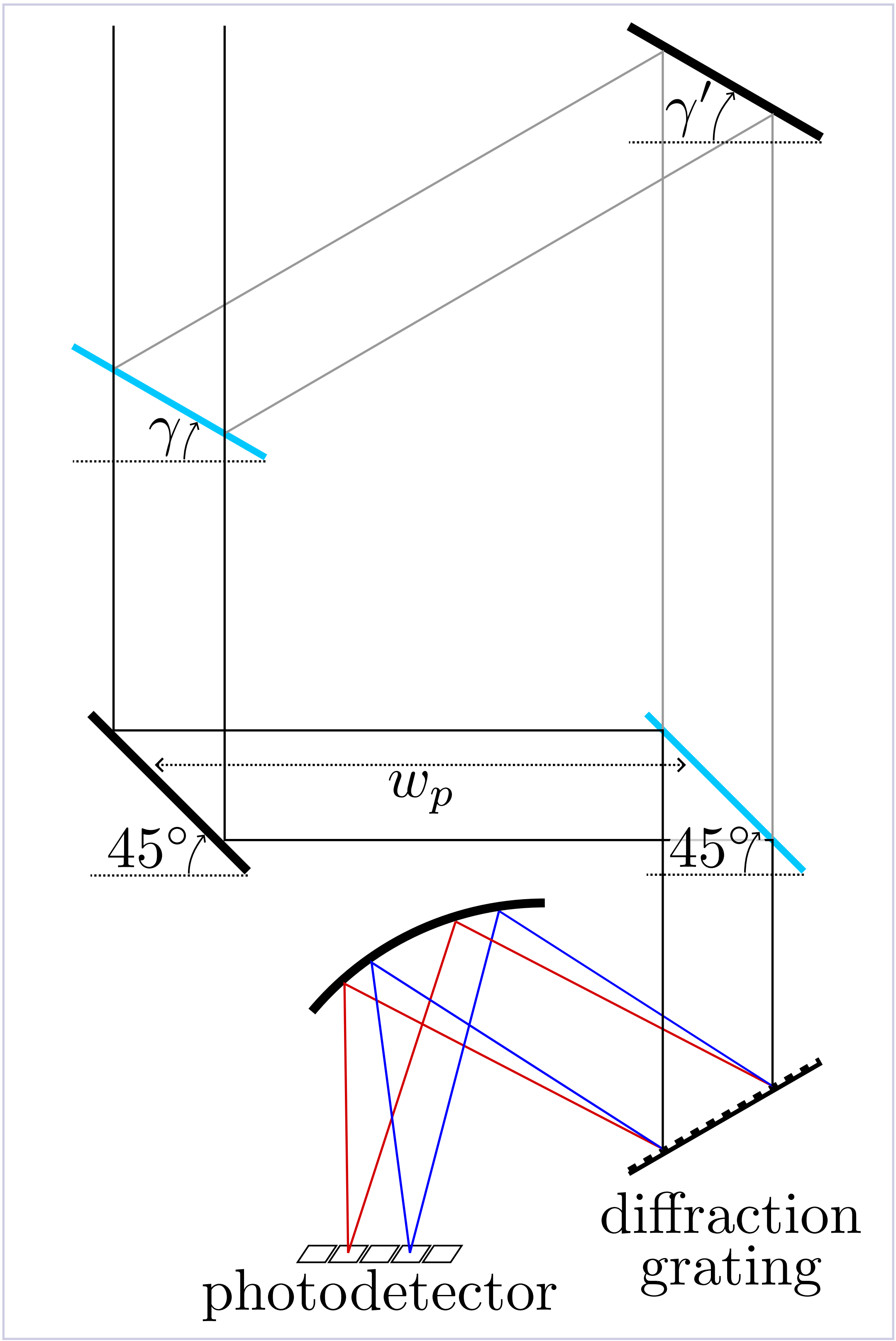


Extended Path Intensity Correlation

One Source







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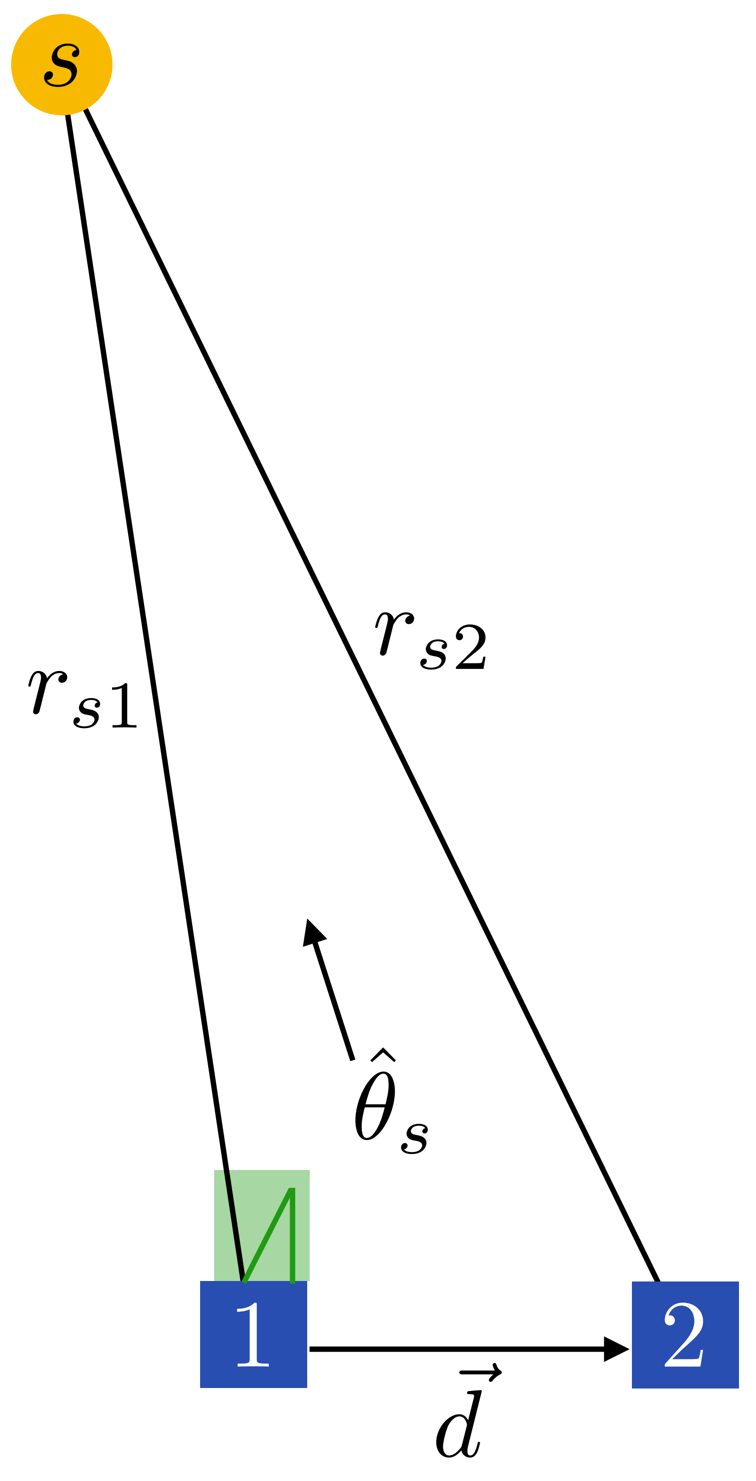

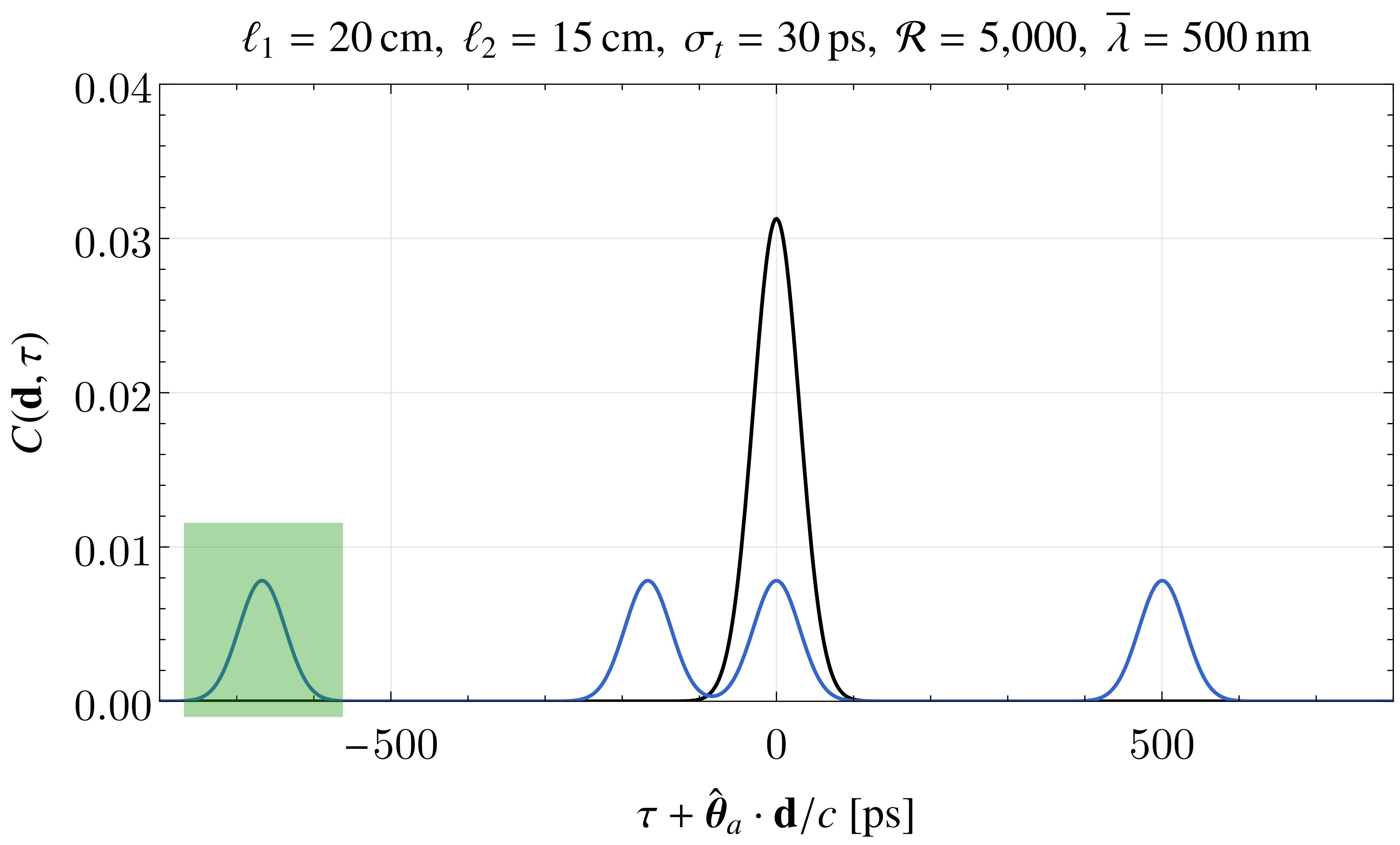

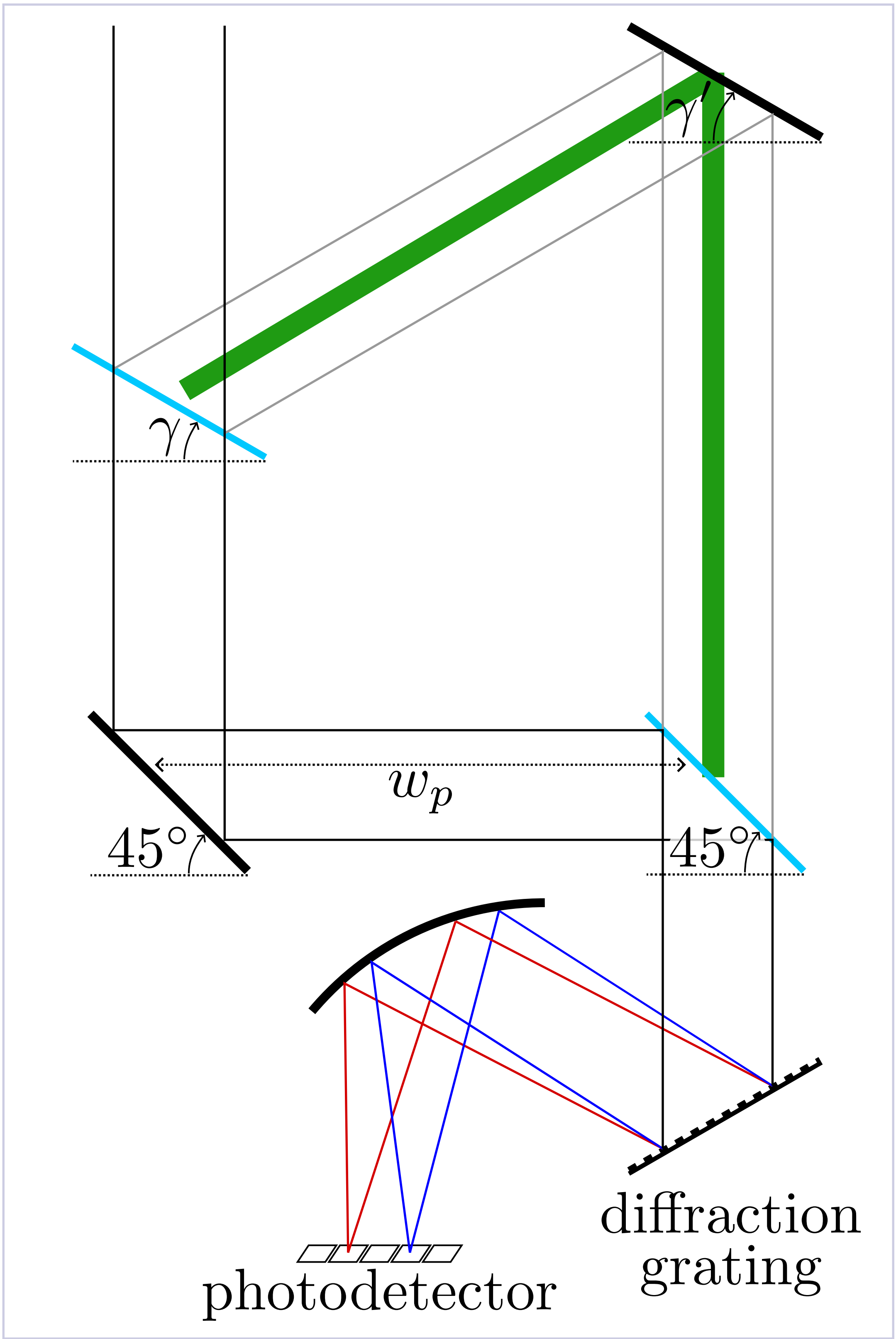

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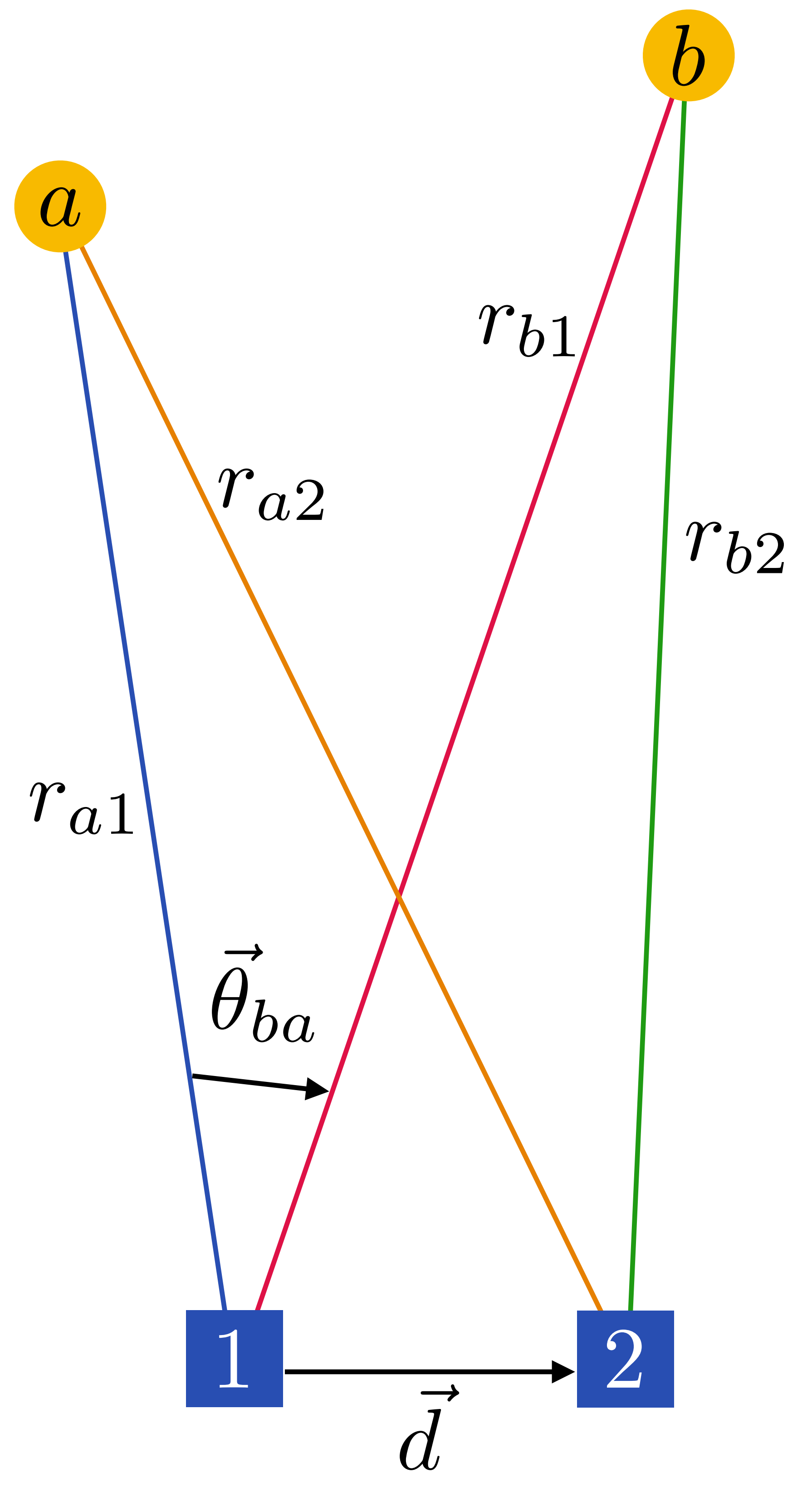

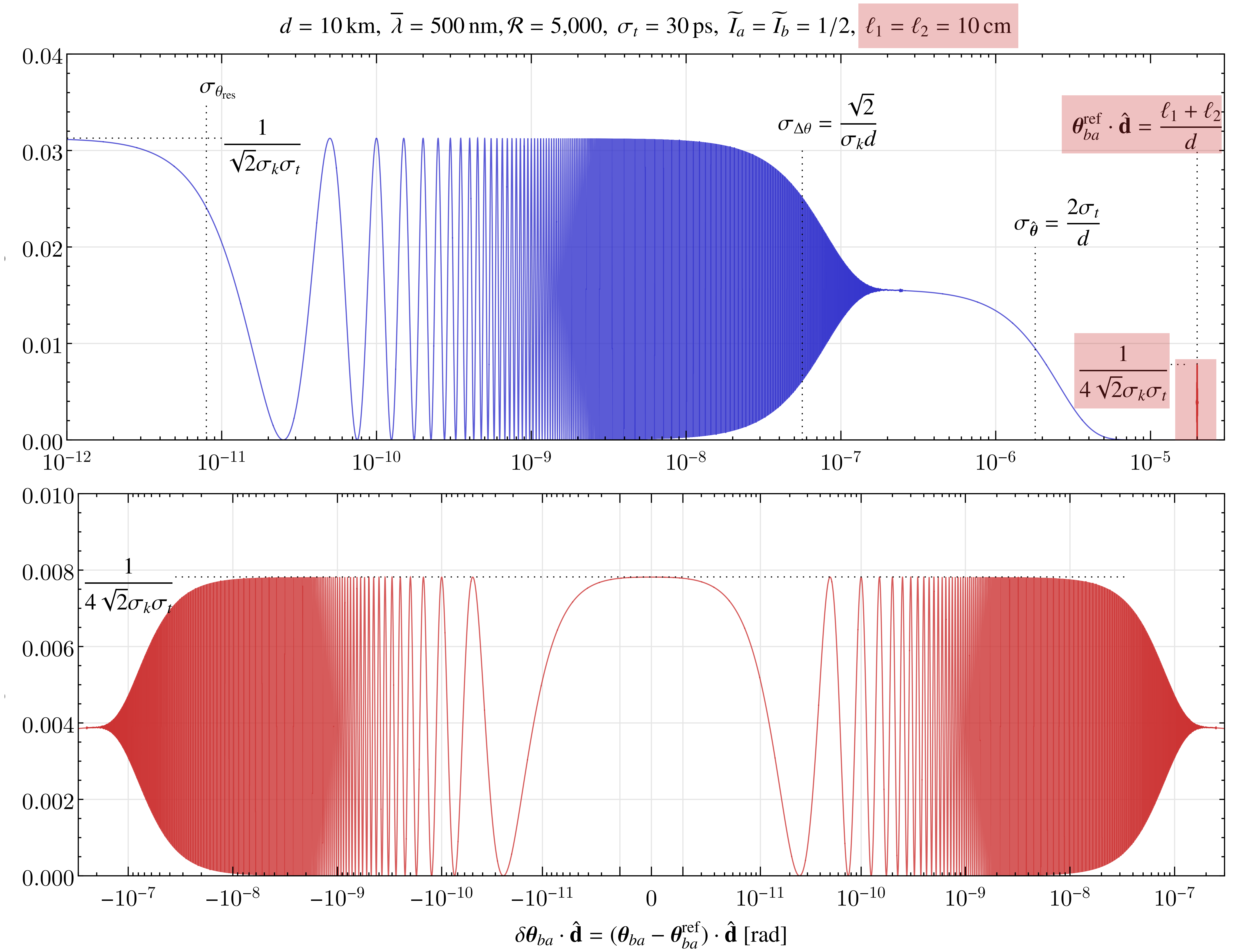

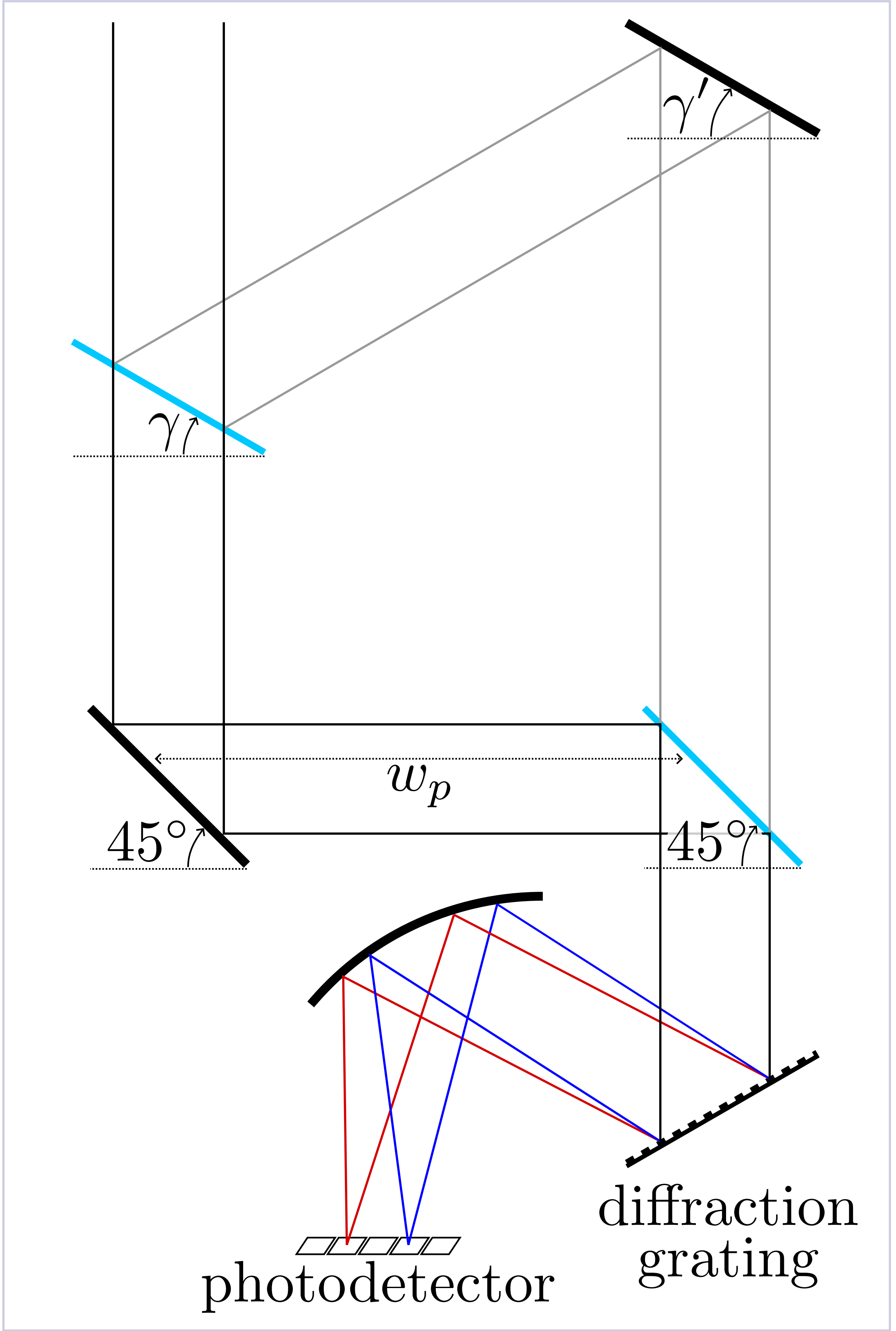

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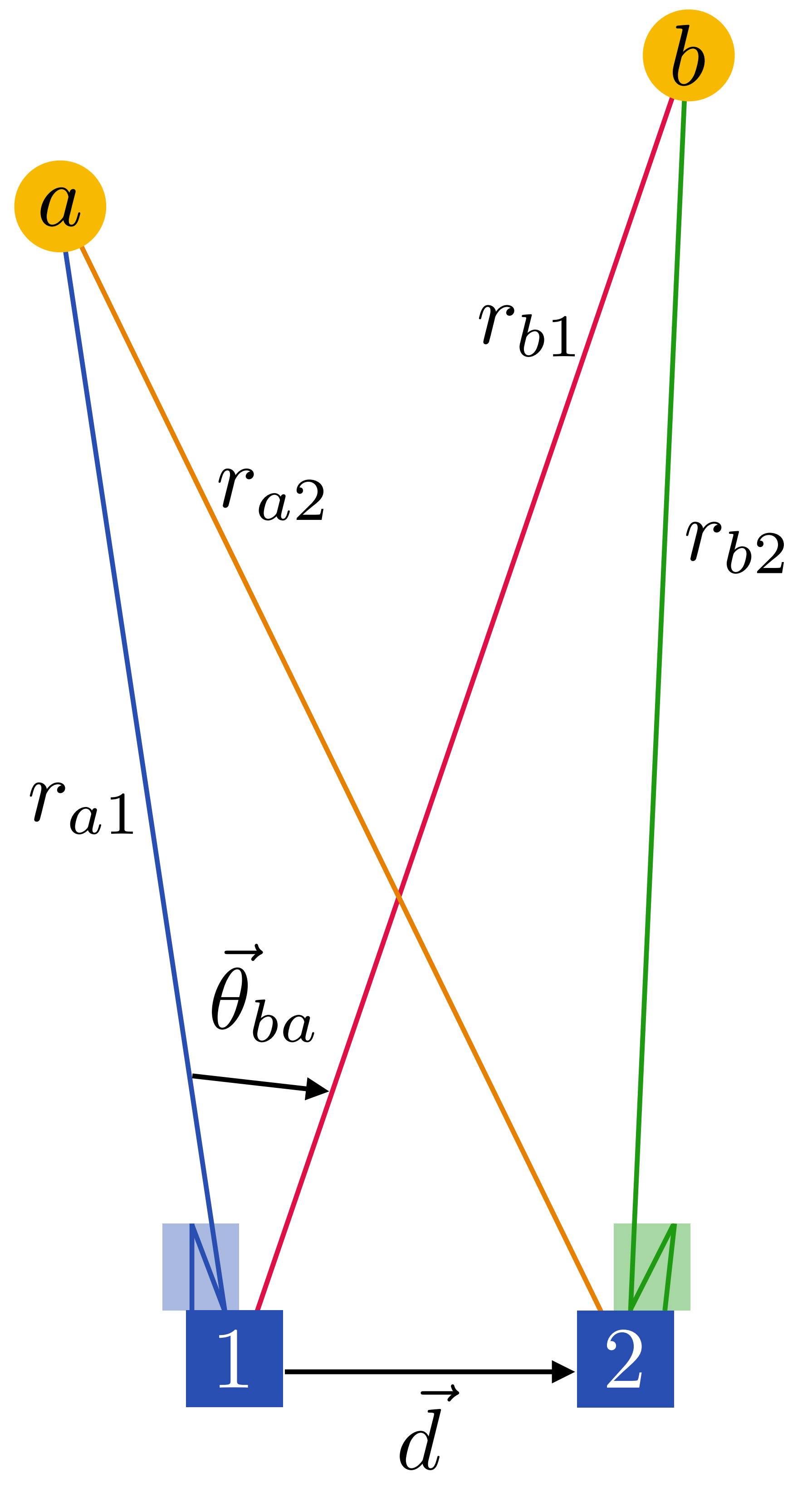
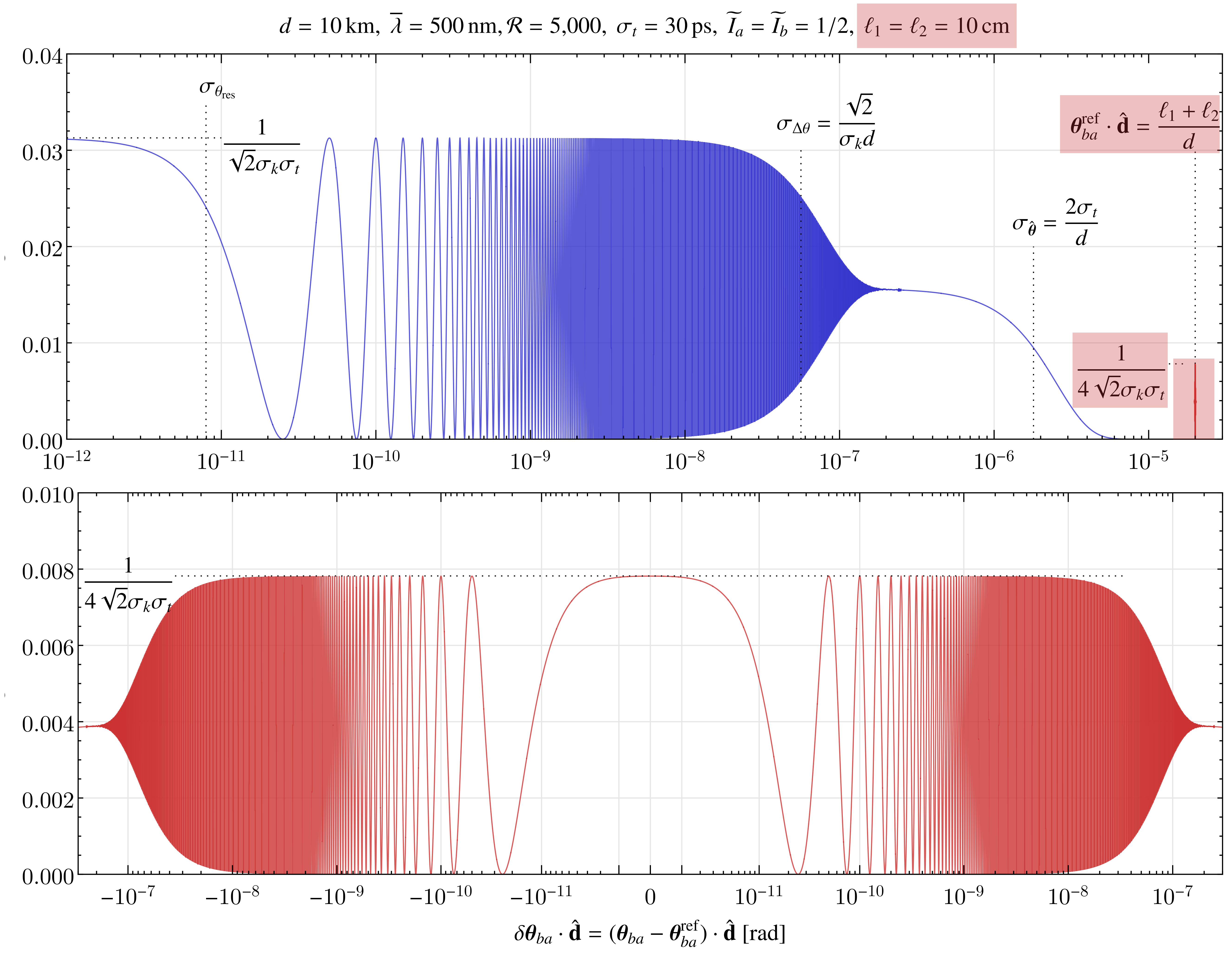
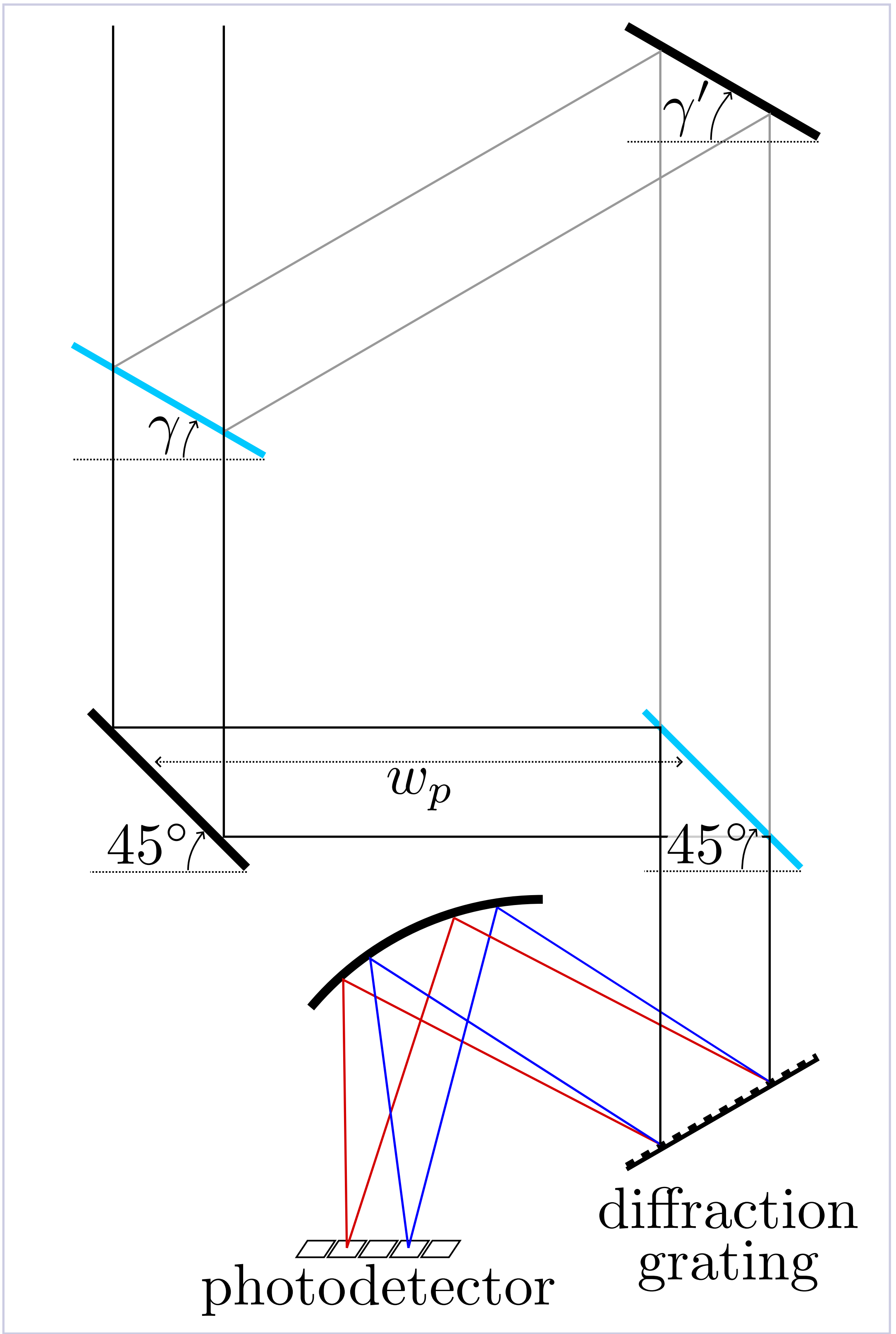


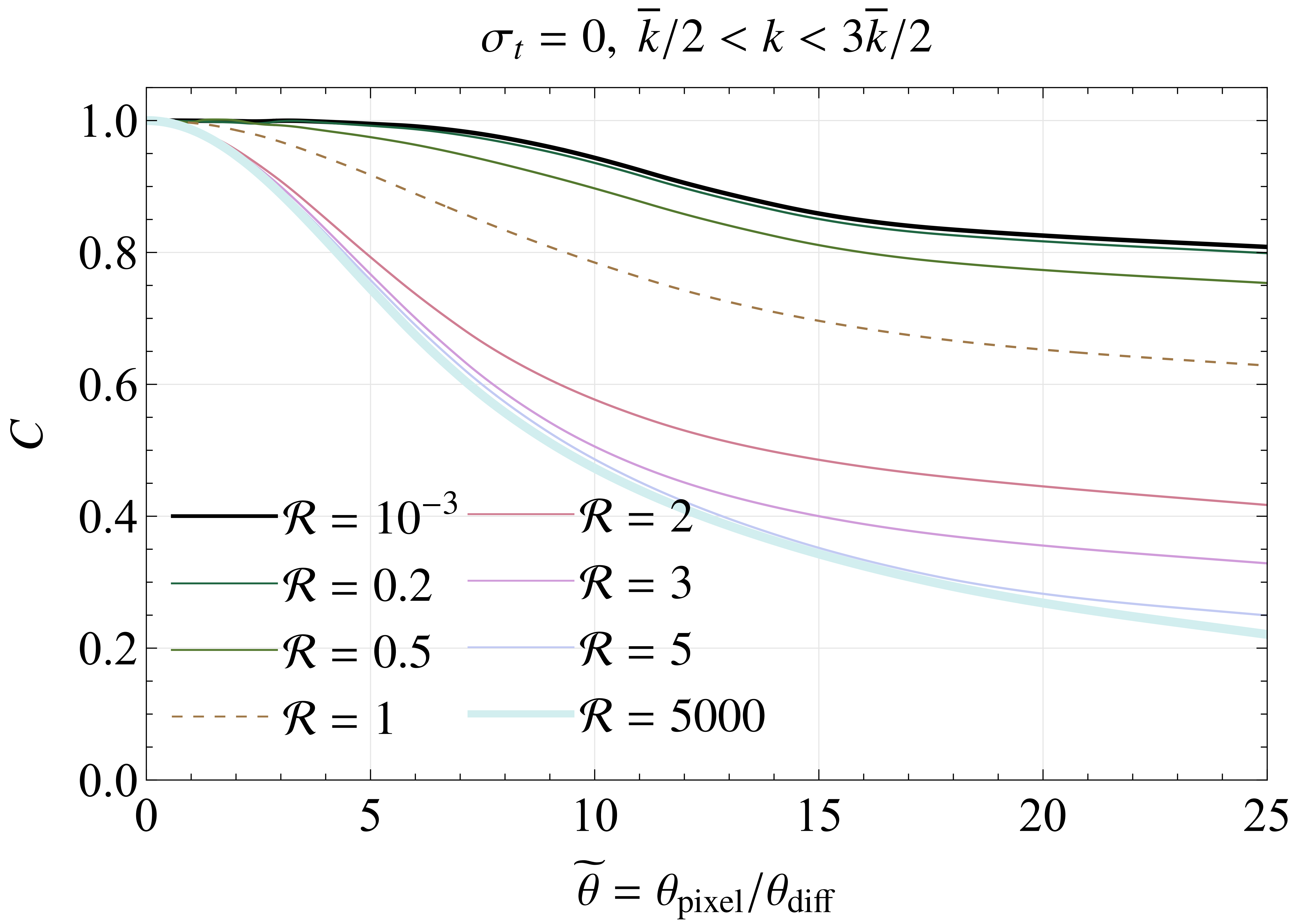


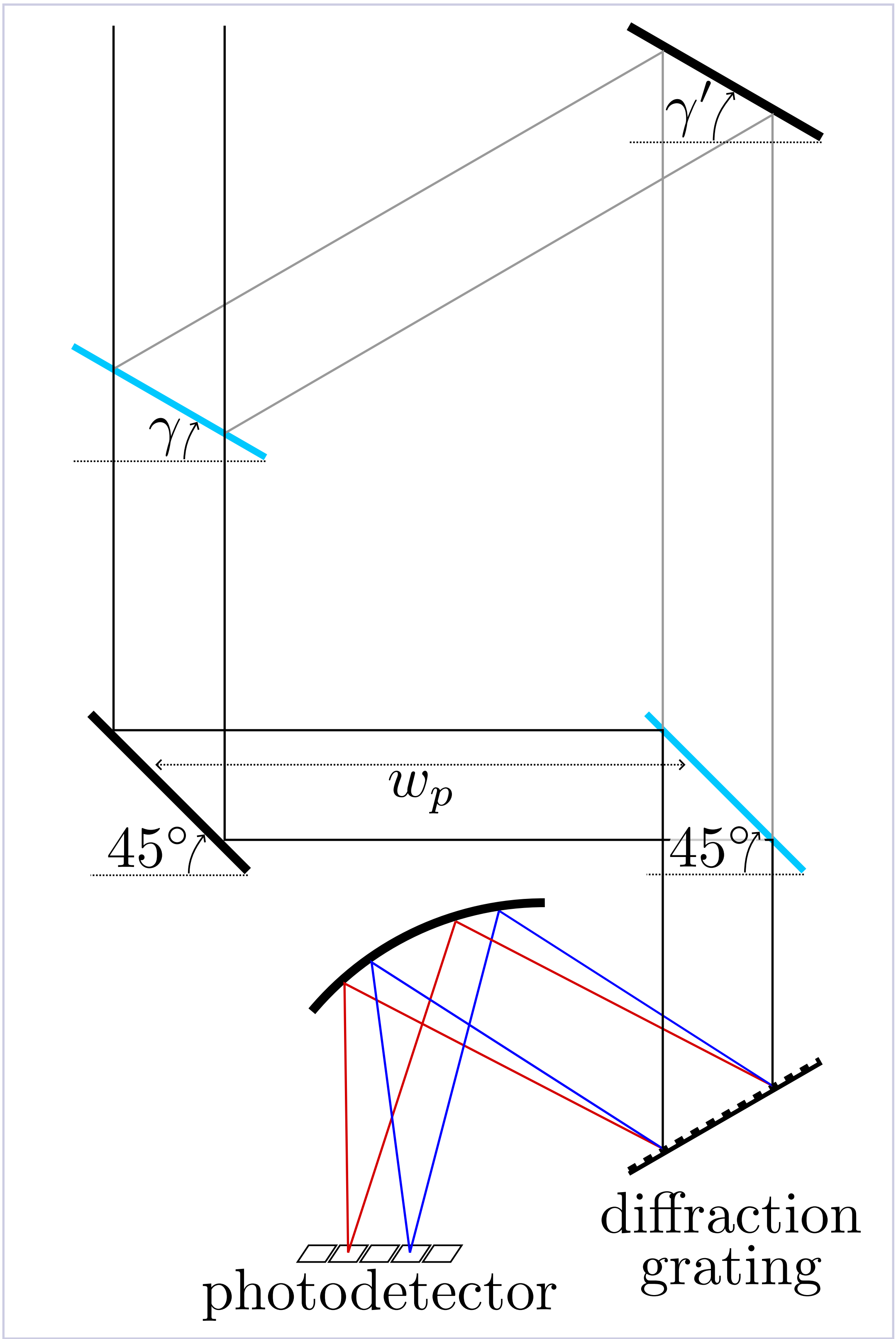


Future Phases of EPIC

	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

Multi-Channel Spectroscopy





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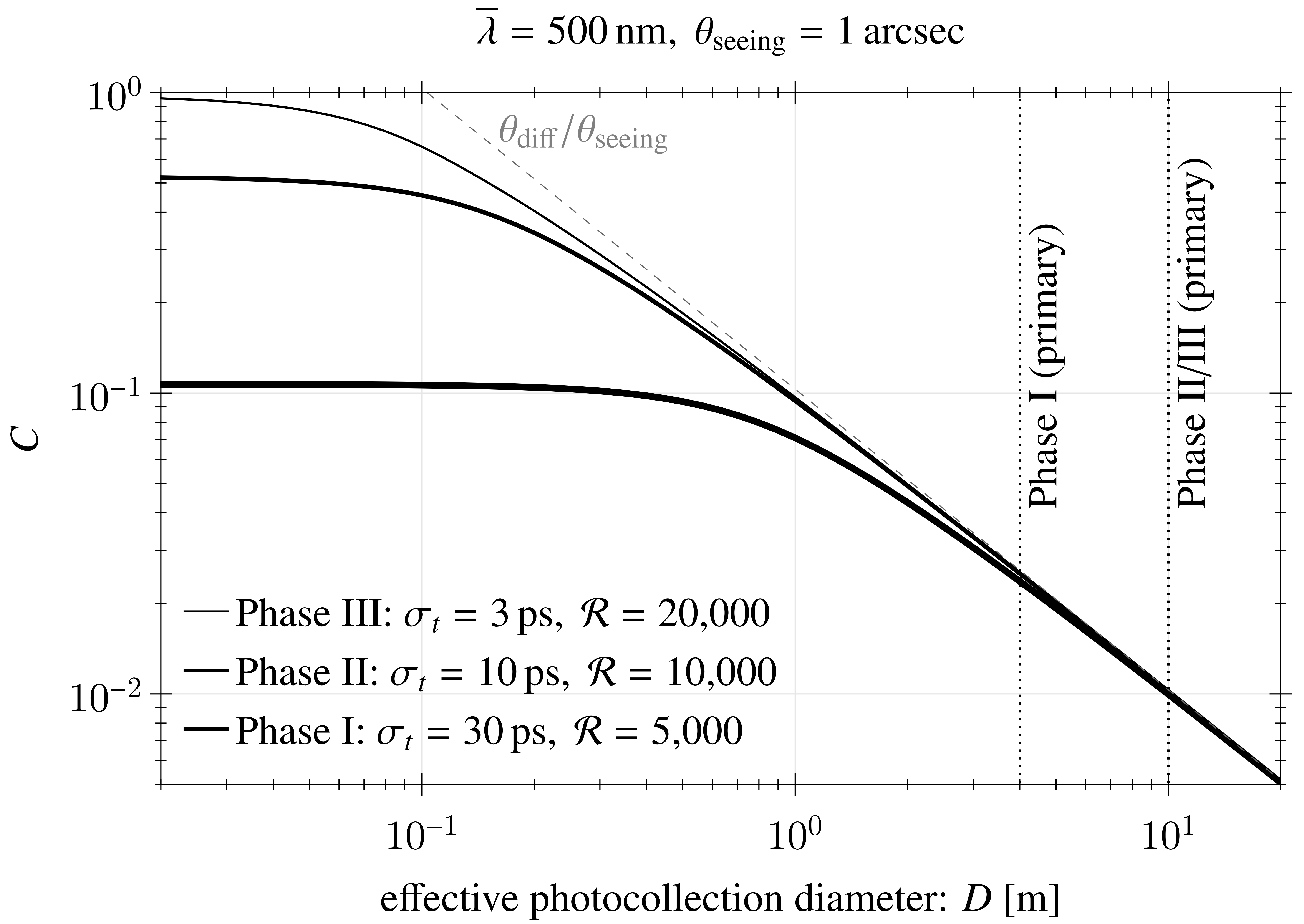
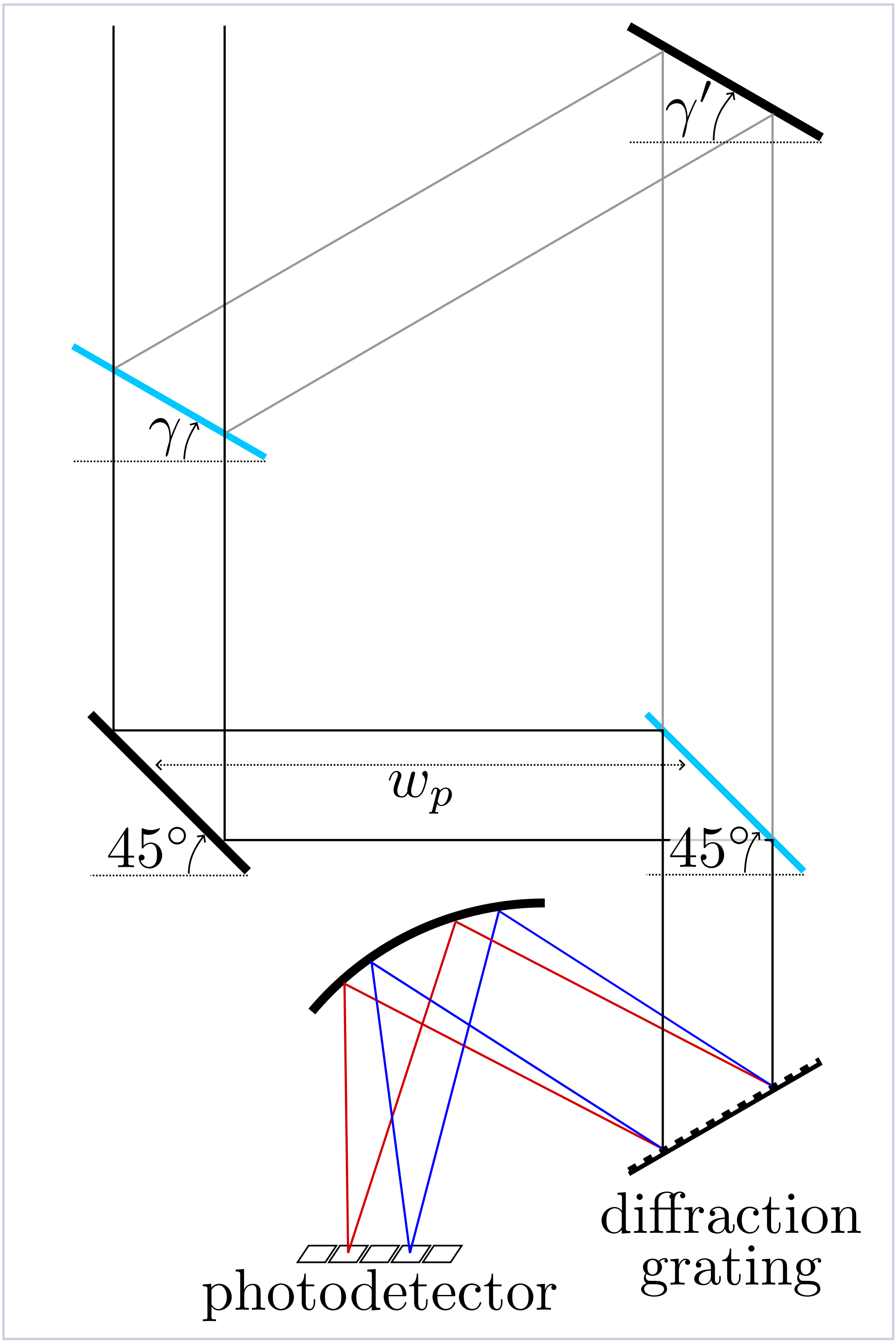
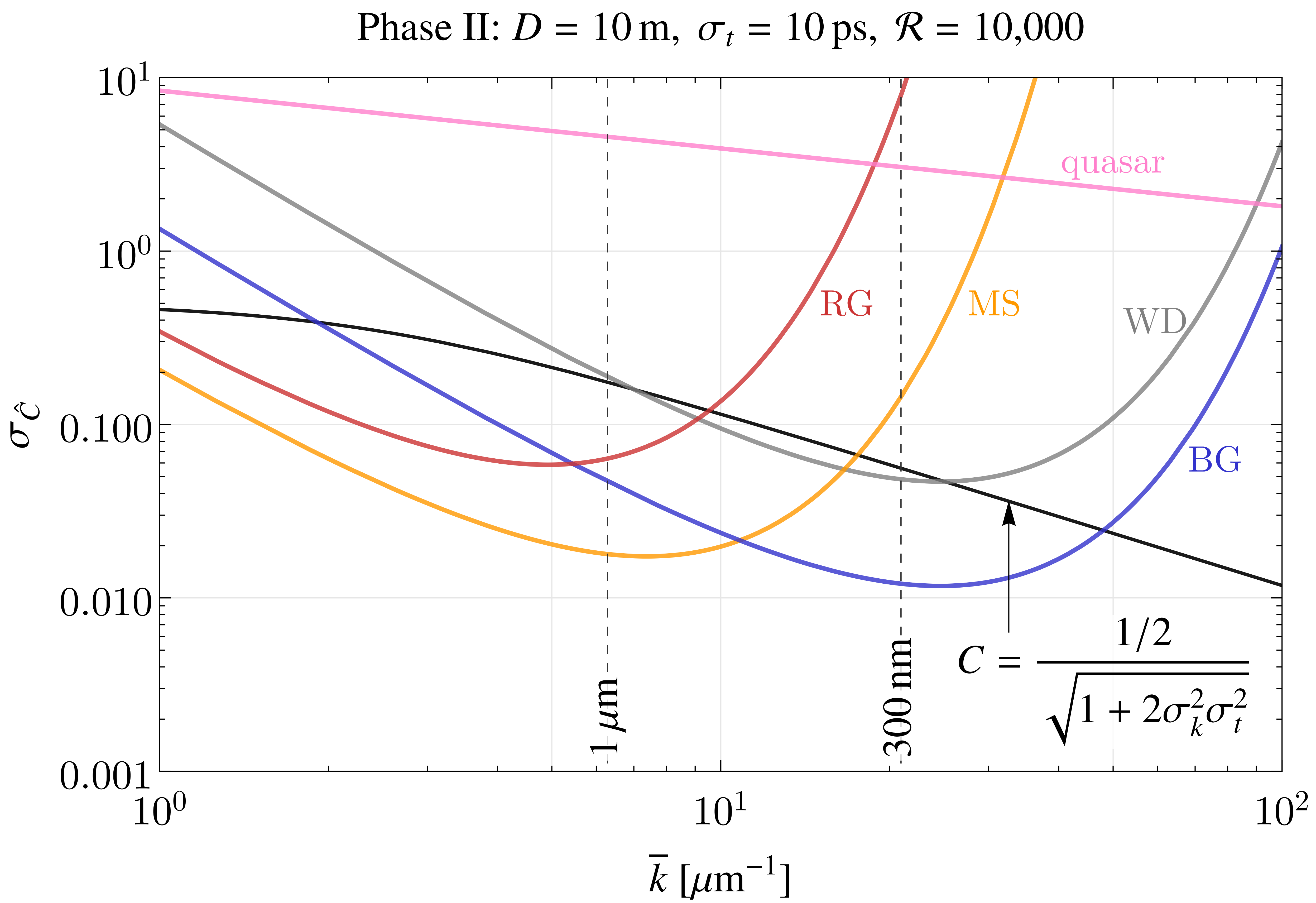
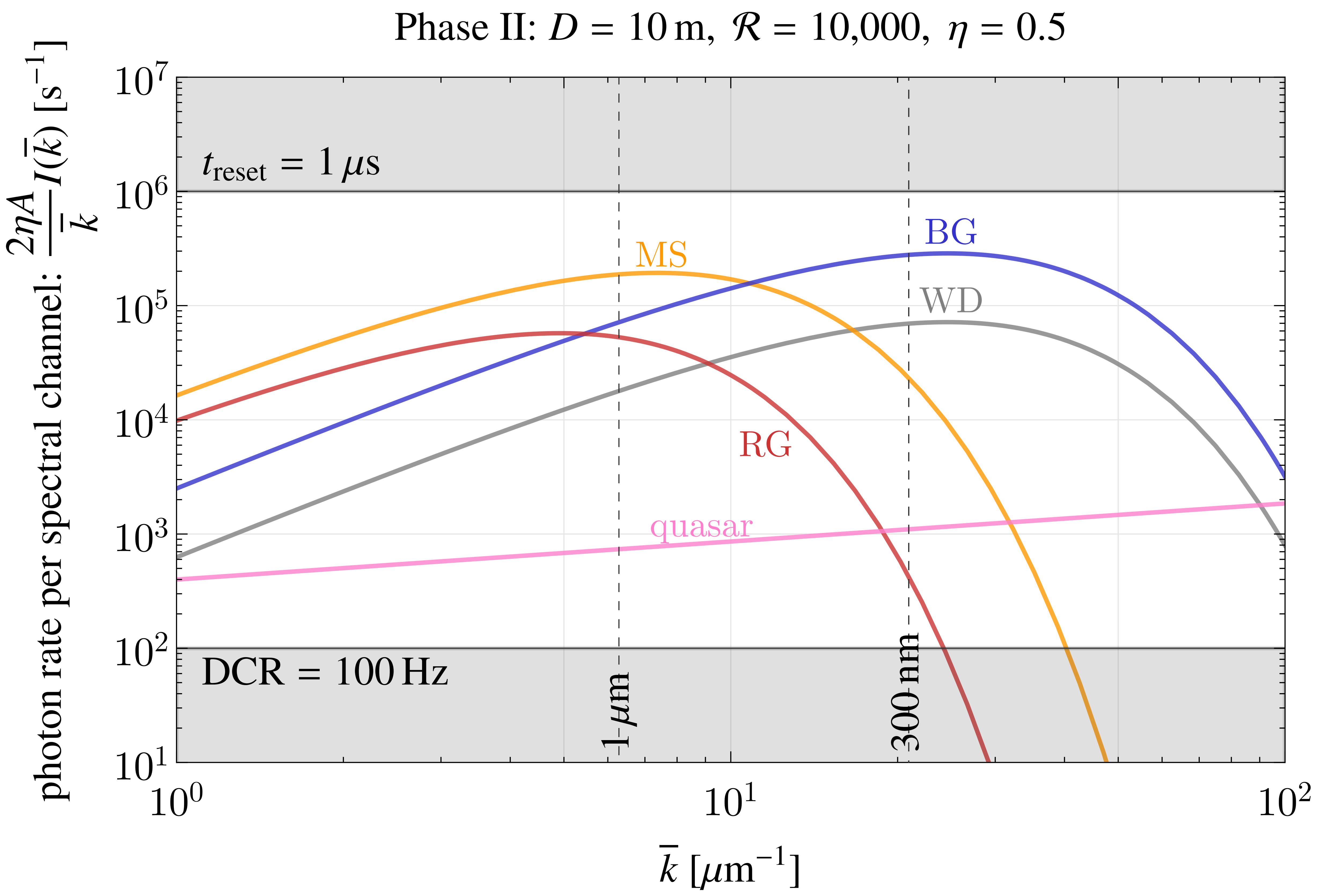




Signal-to-Noise Ratio

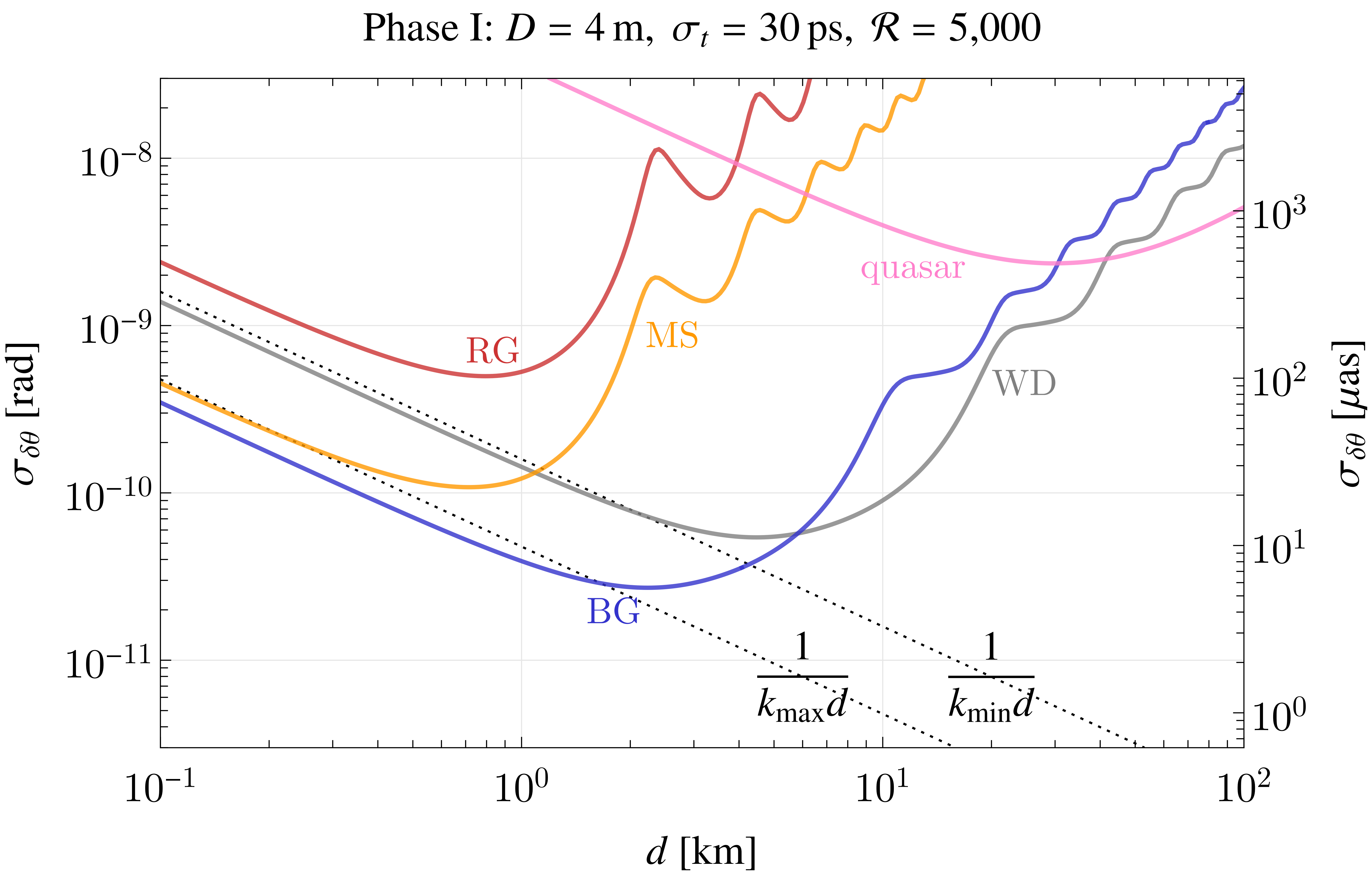




Light-Centroiding Precision

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

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



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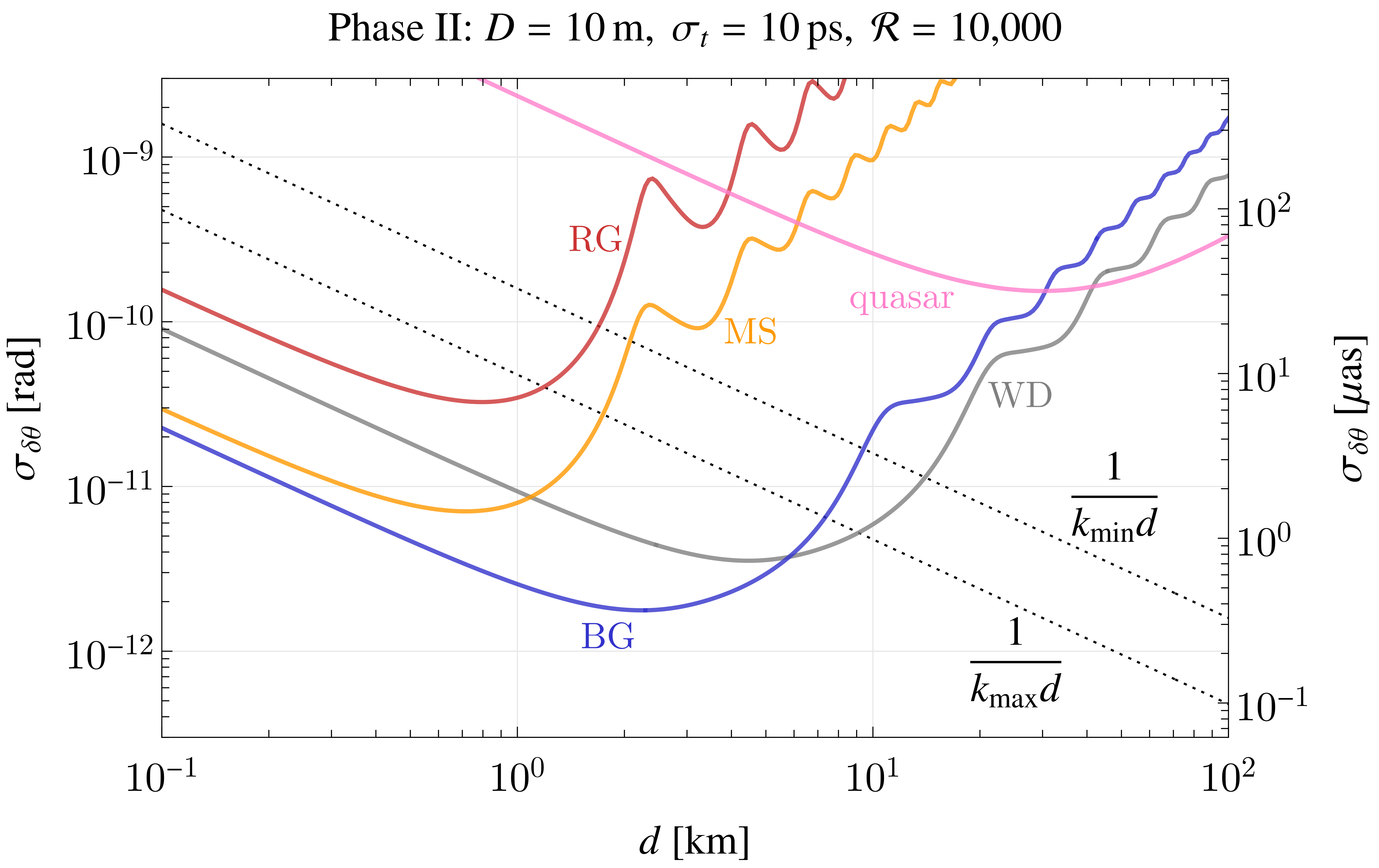

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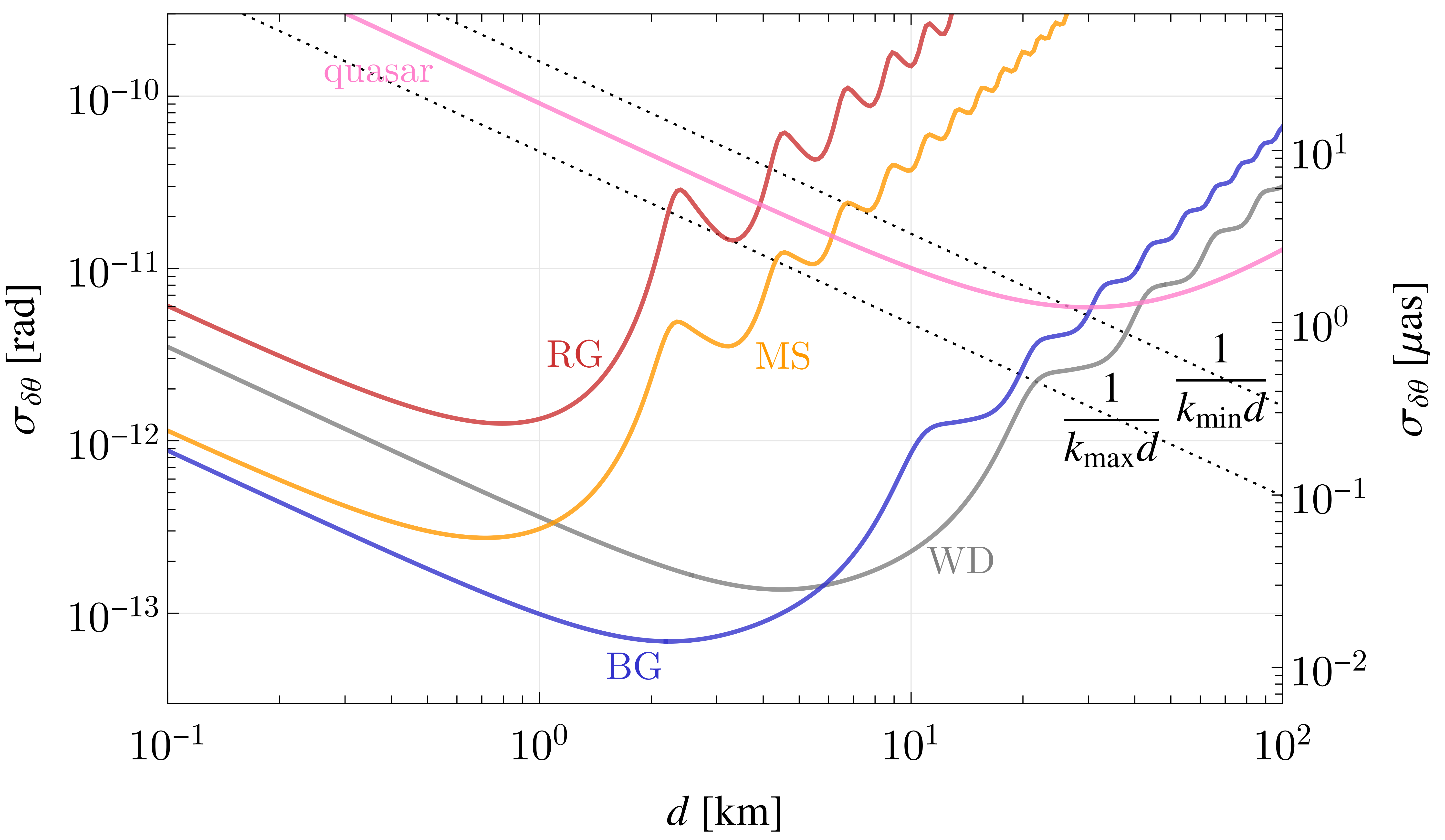
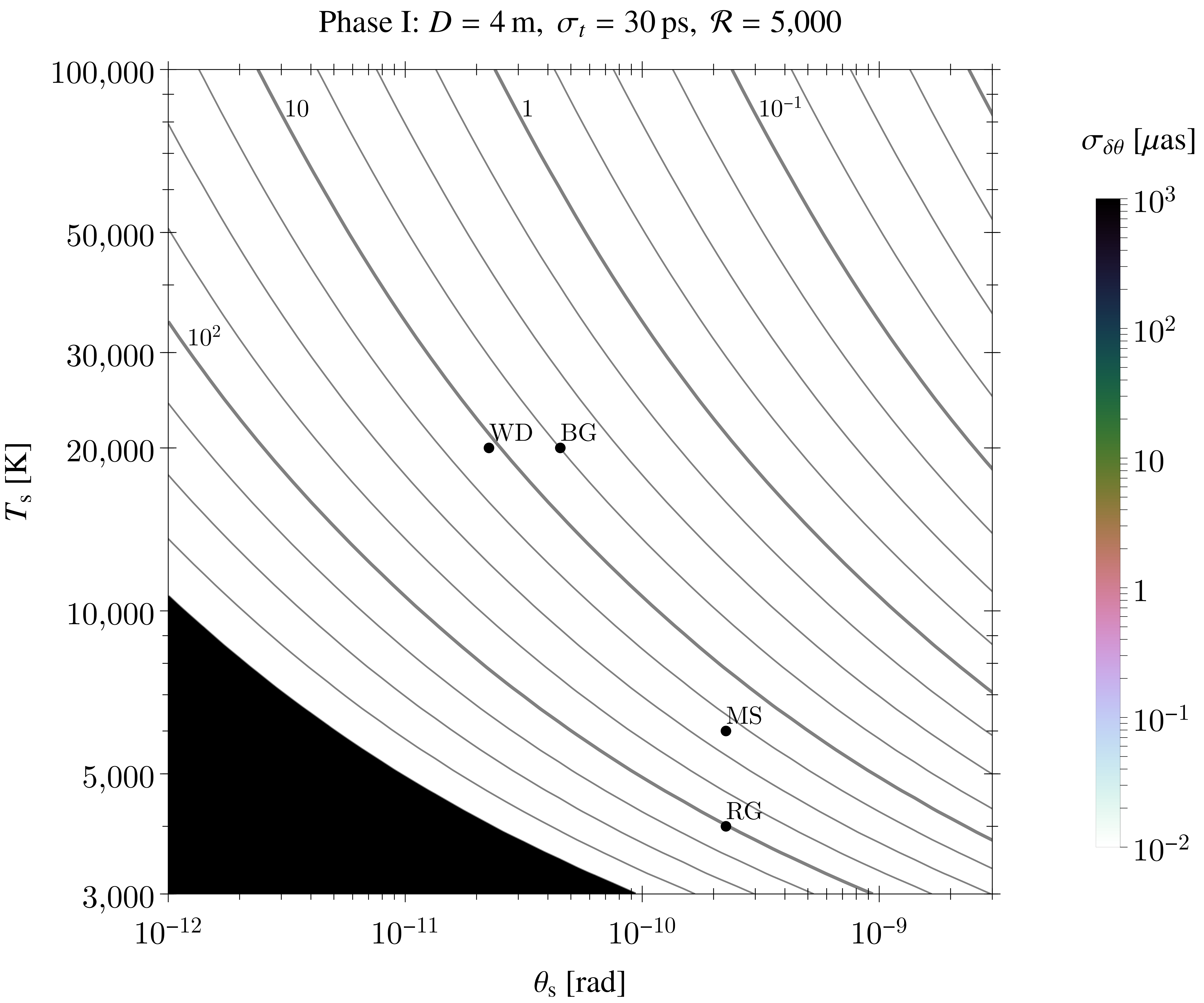
Phase III: $D = 10\,{\rm m}$, $\sigma_t = 3\,{\rm ps}$, $\mathcal{R} = 20{,}000$, $n_{\rm arr} = 10$

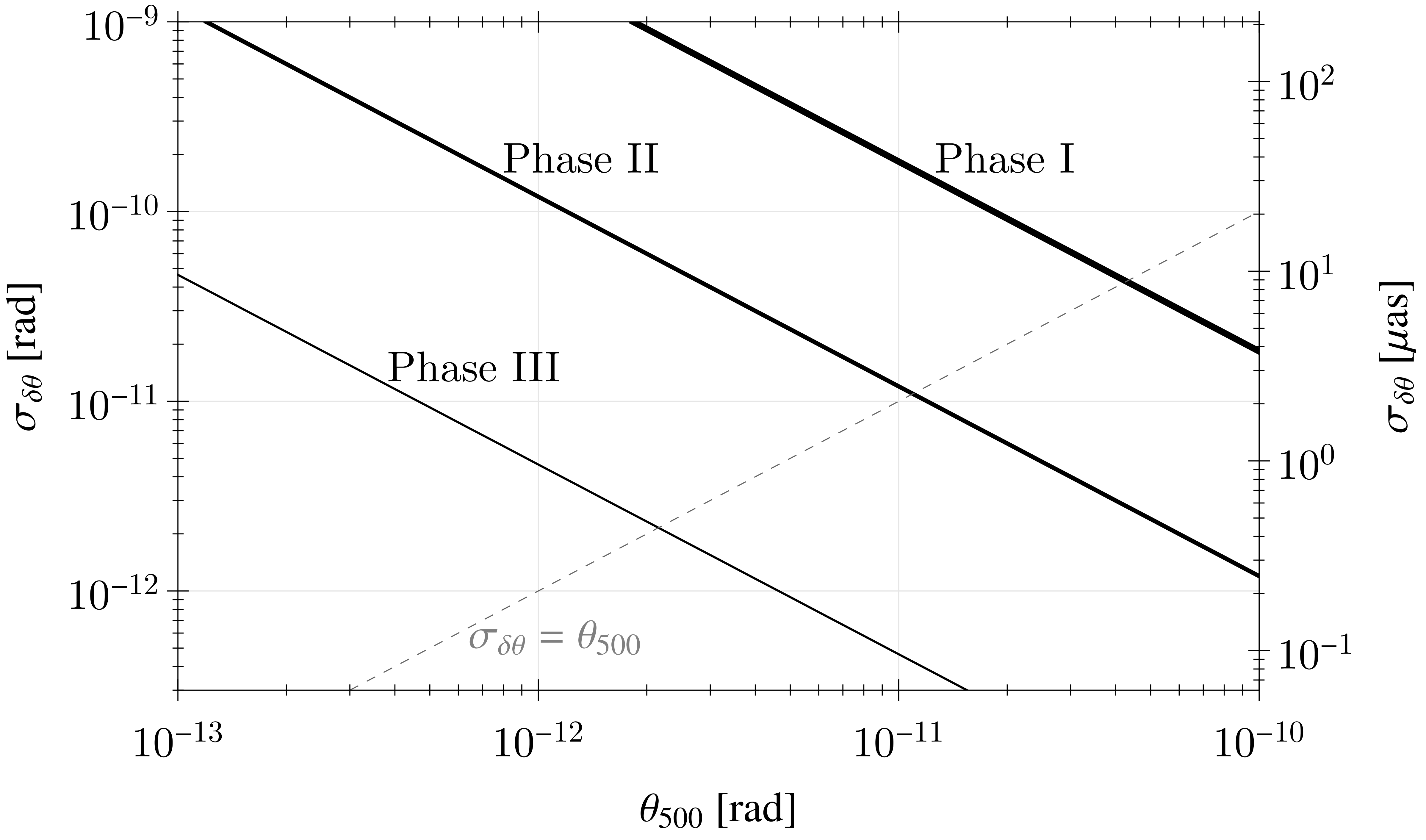


Light-Centroiding Precision

Stars



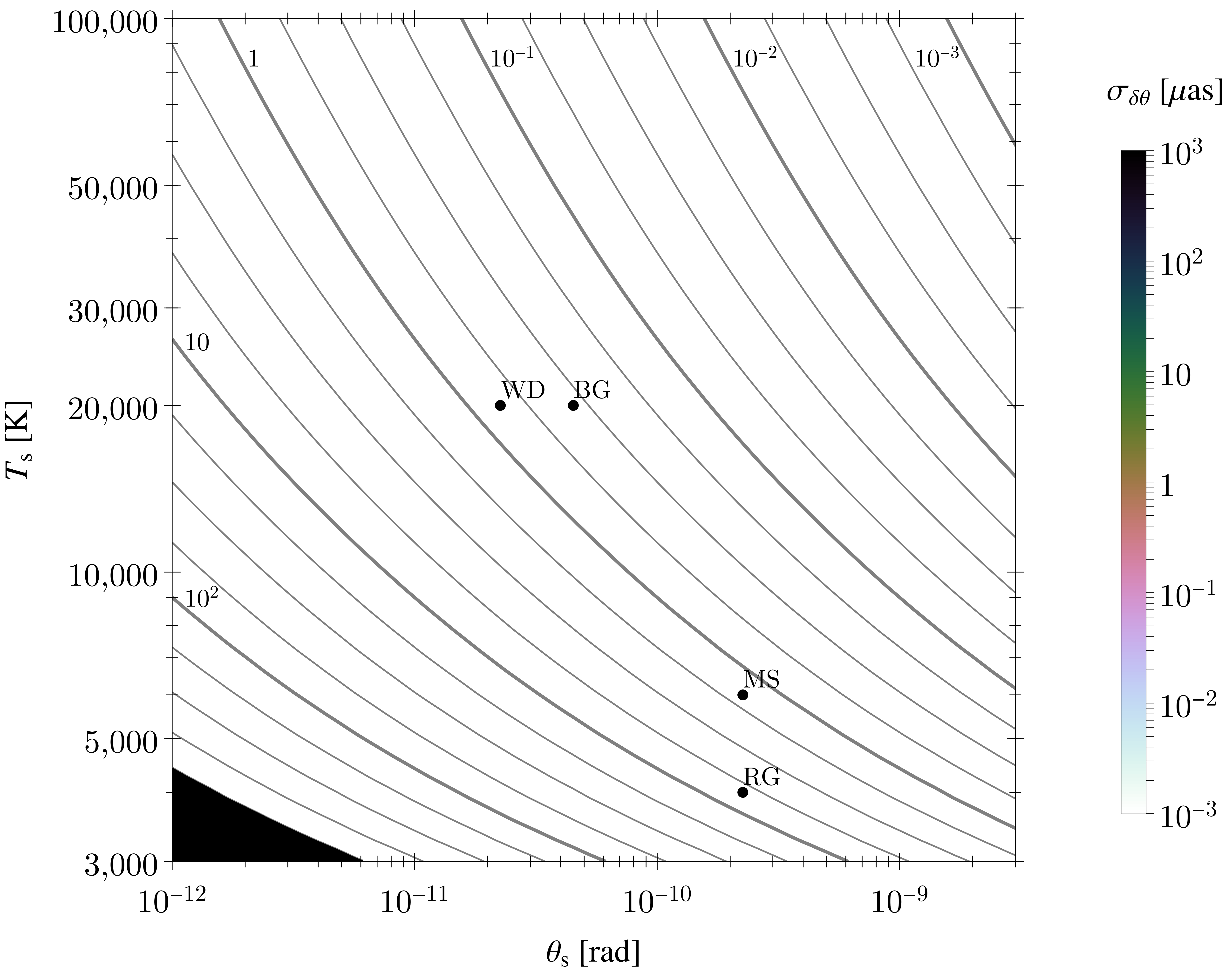
Quasars



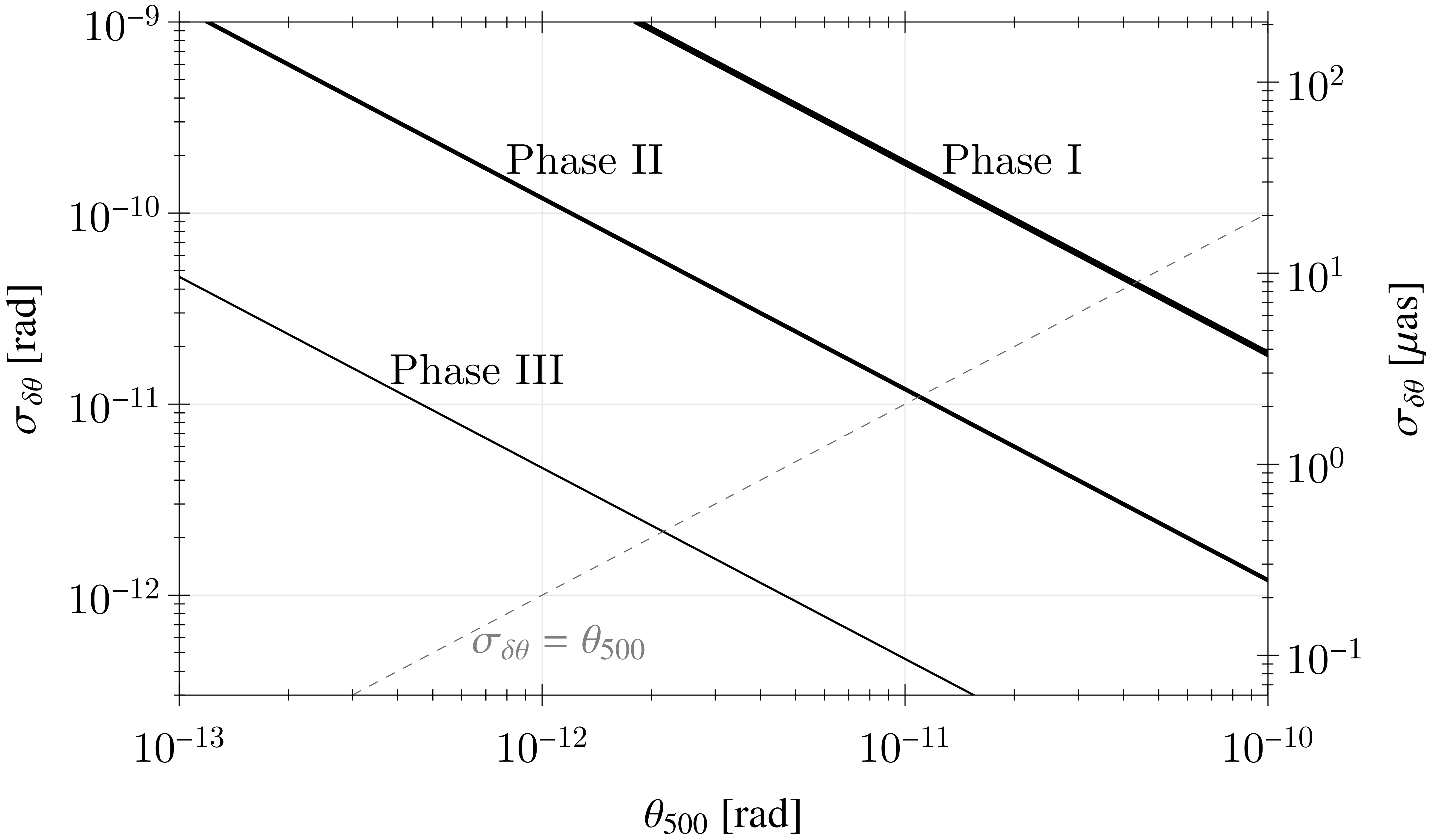
Light-Centroiding Precision

Stars

Phase II: D = 10 m, σ_t = 10 ps, $\mathcal{R}$ = 10,000



Quasars



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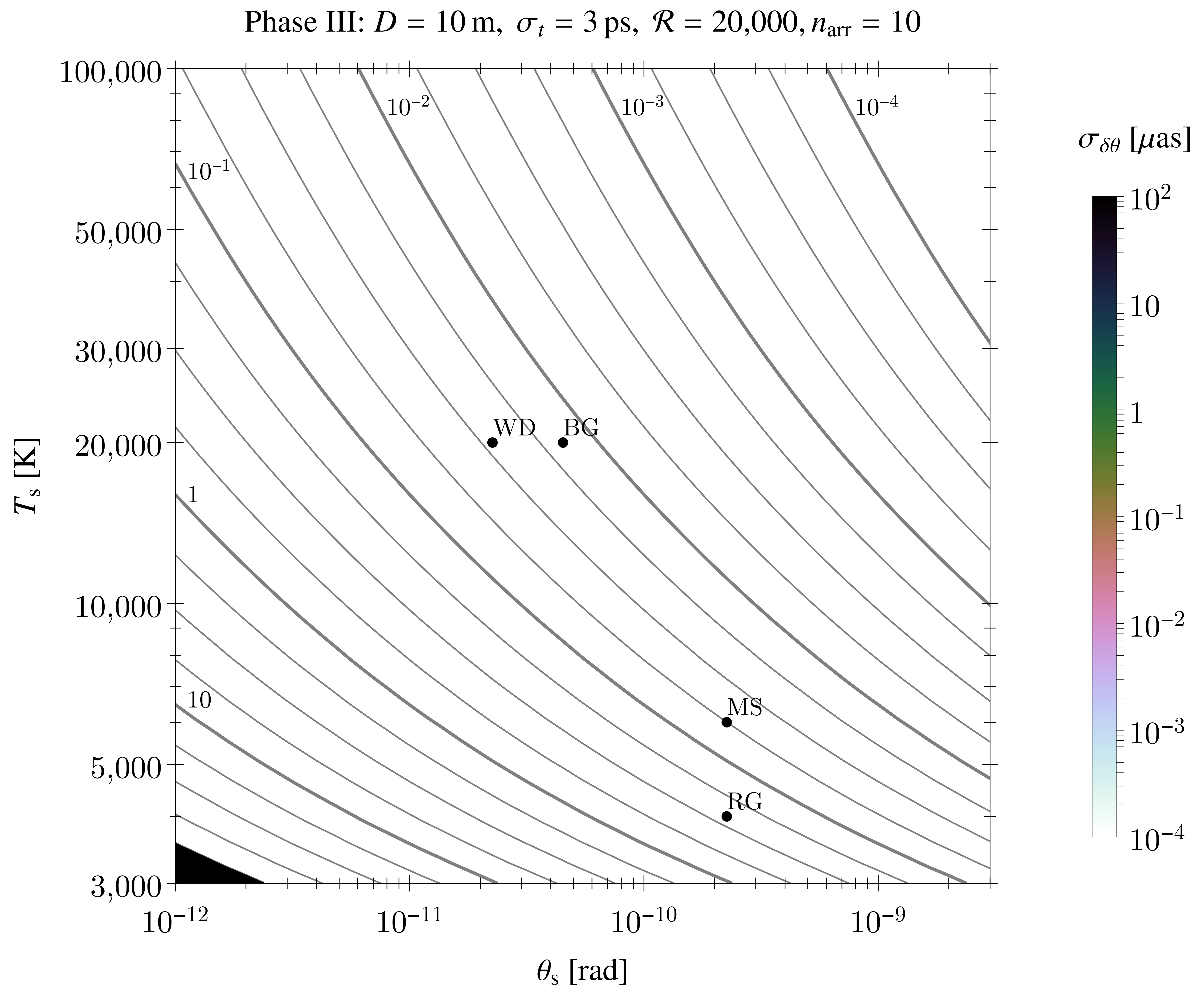

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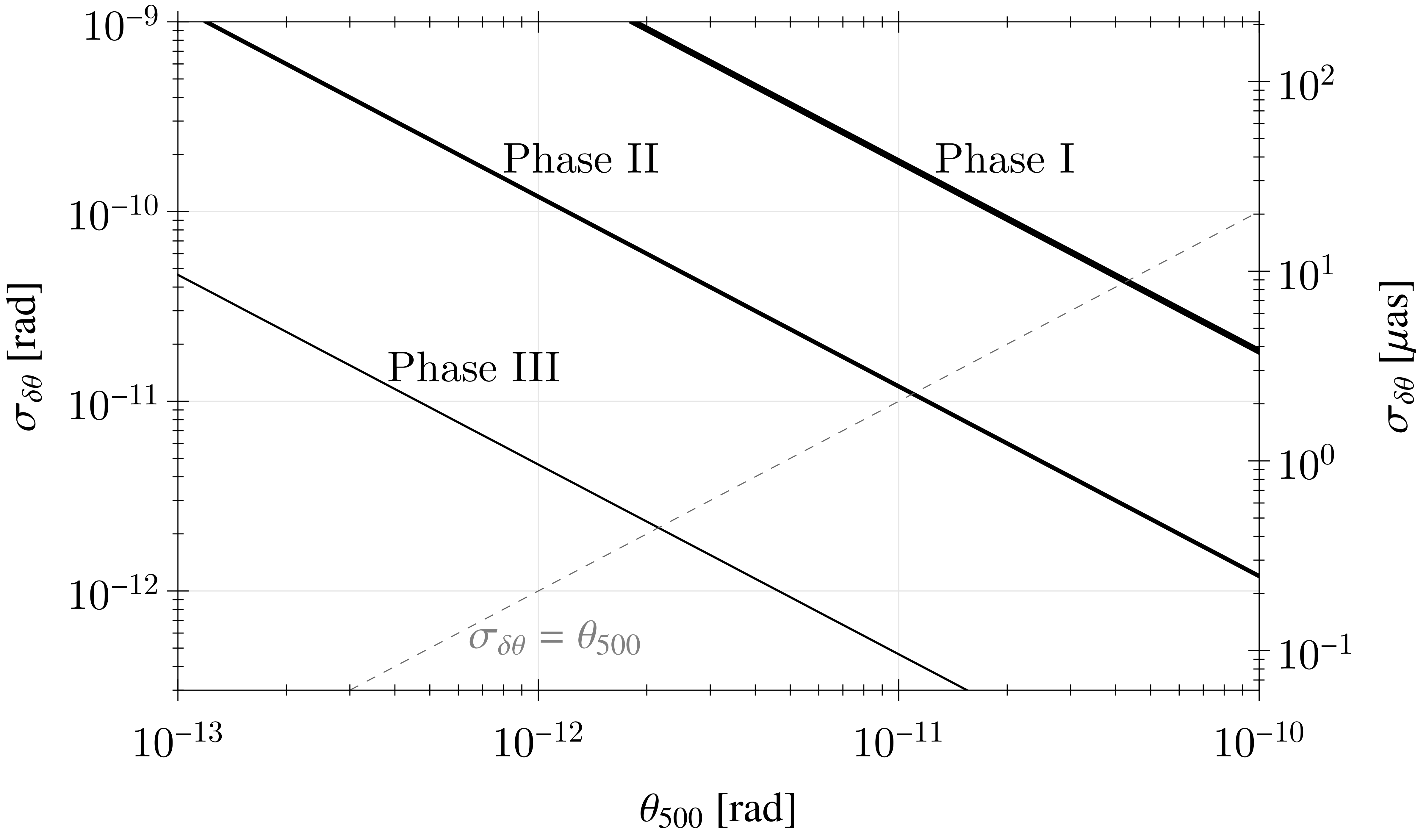
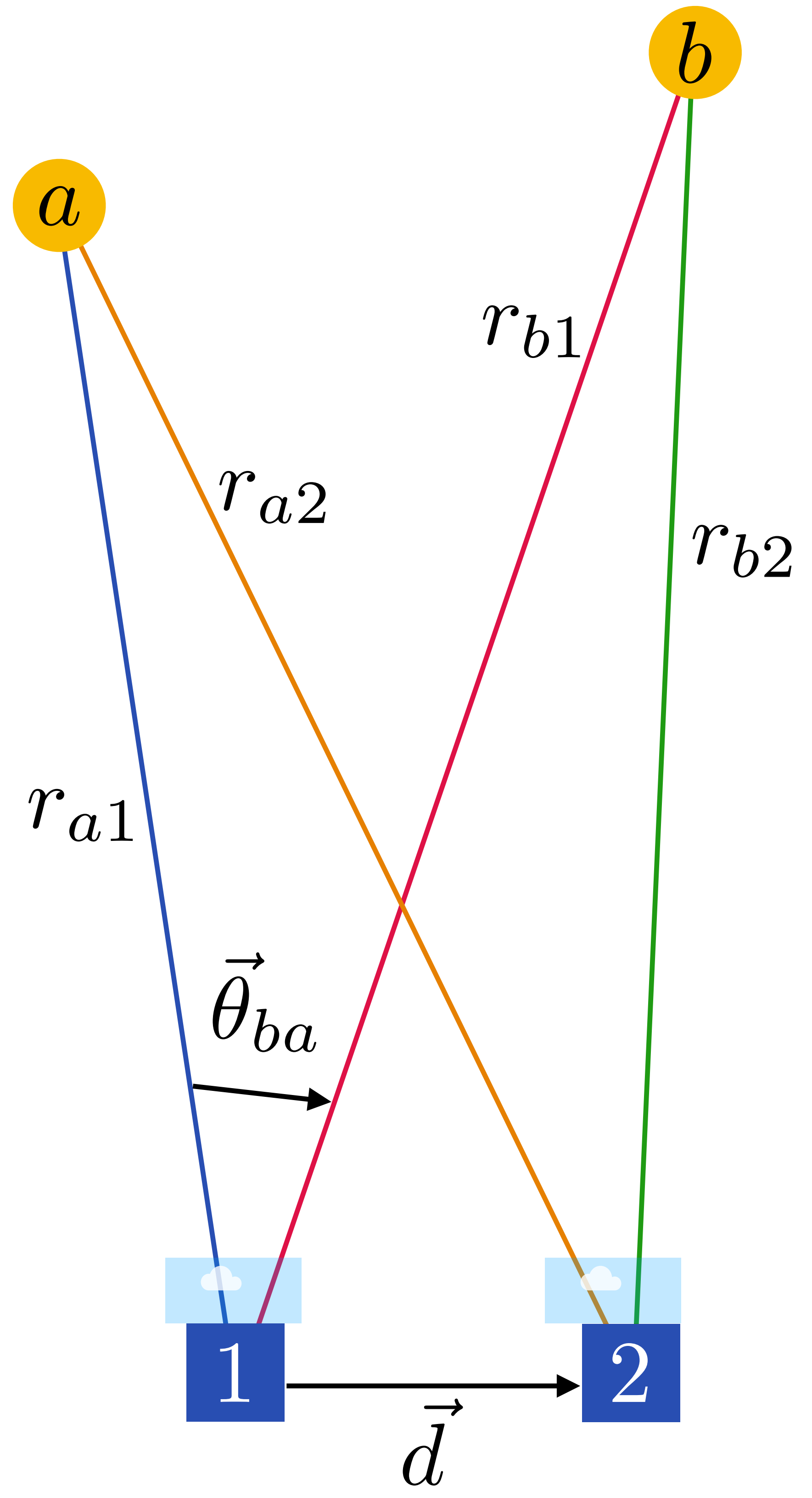
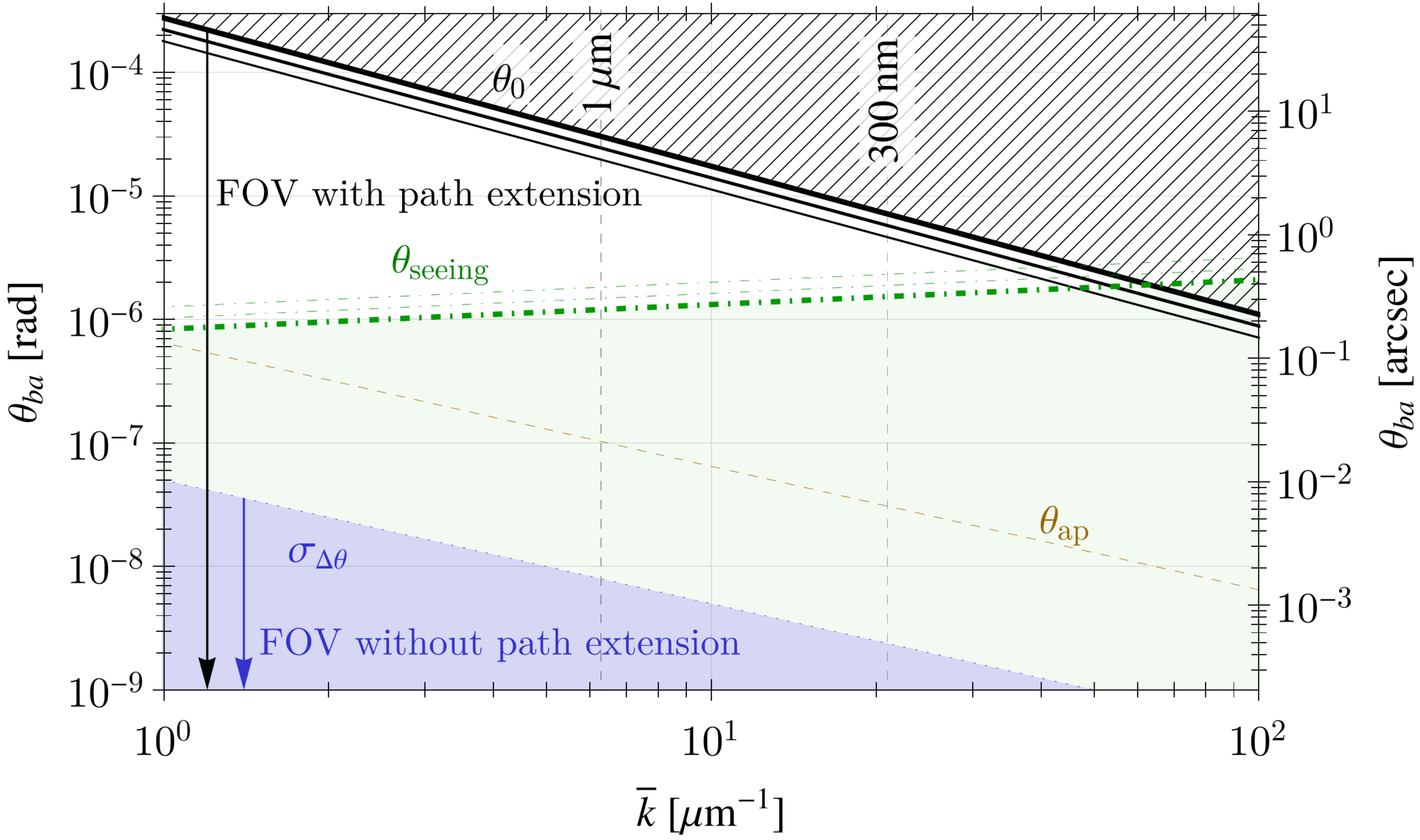
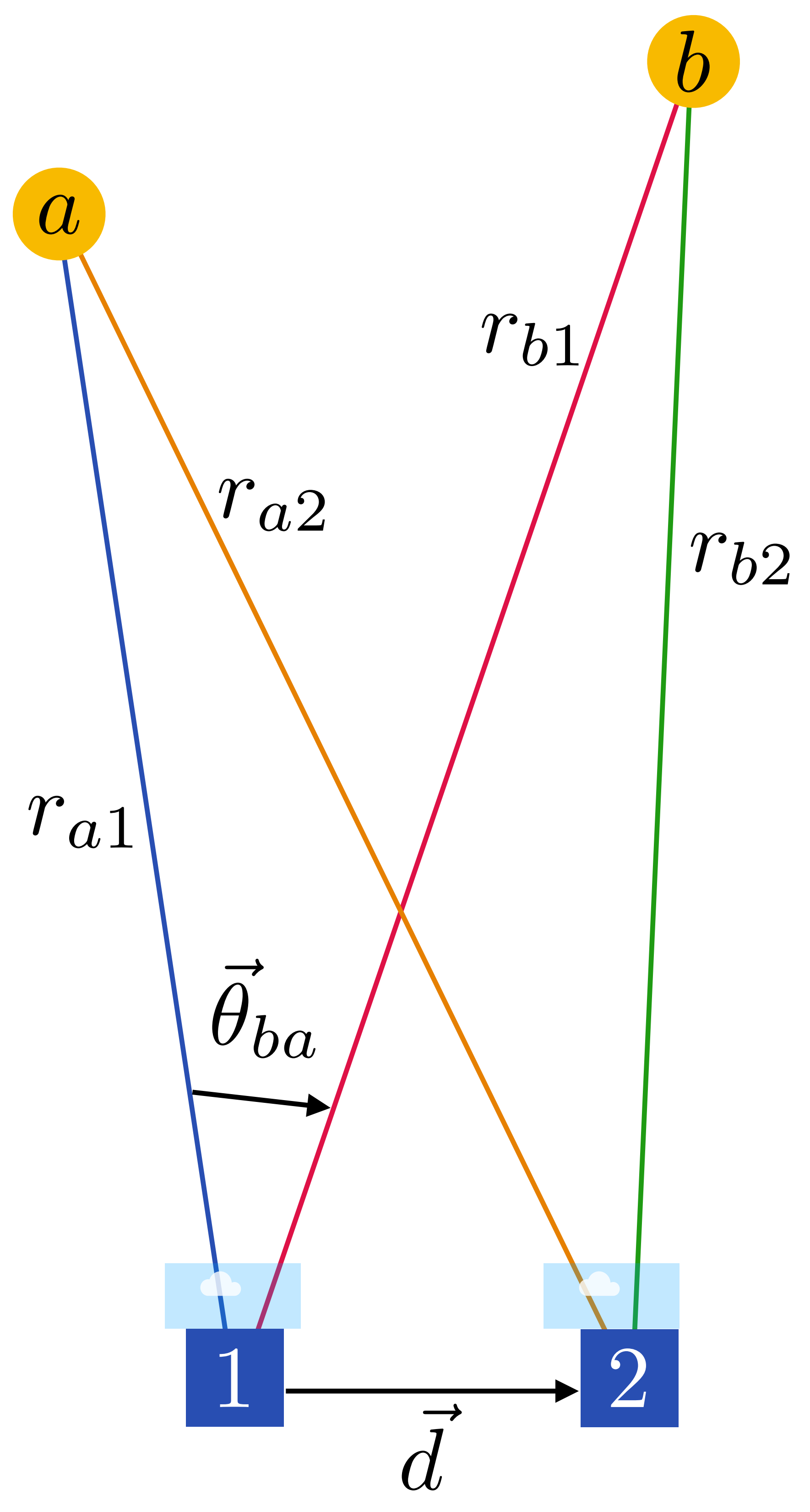


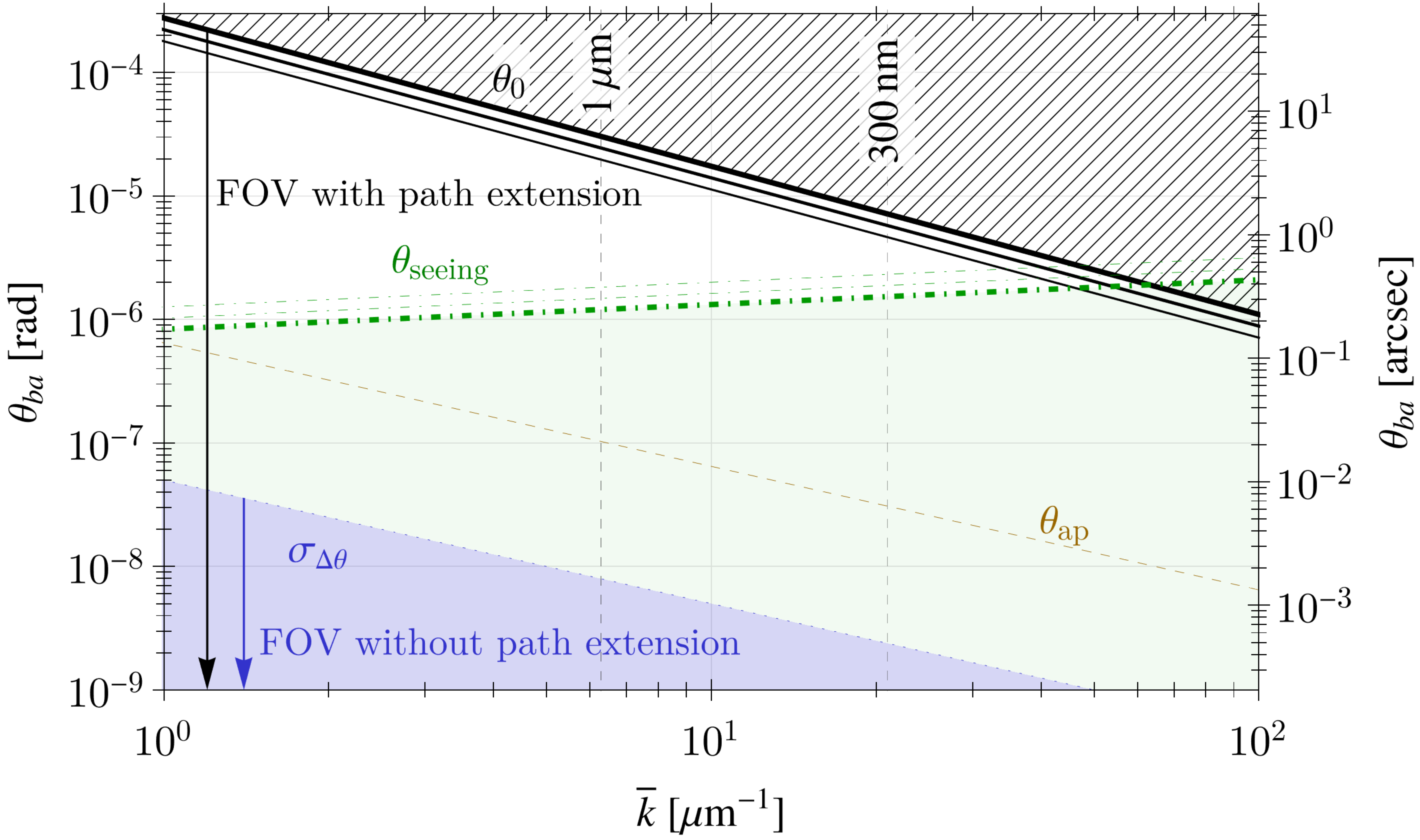
Atmospheric Aberrations



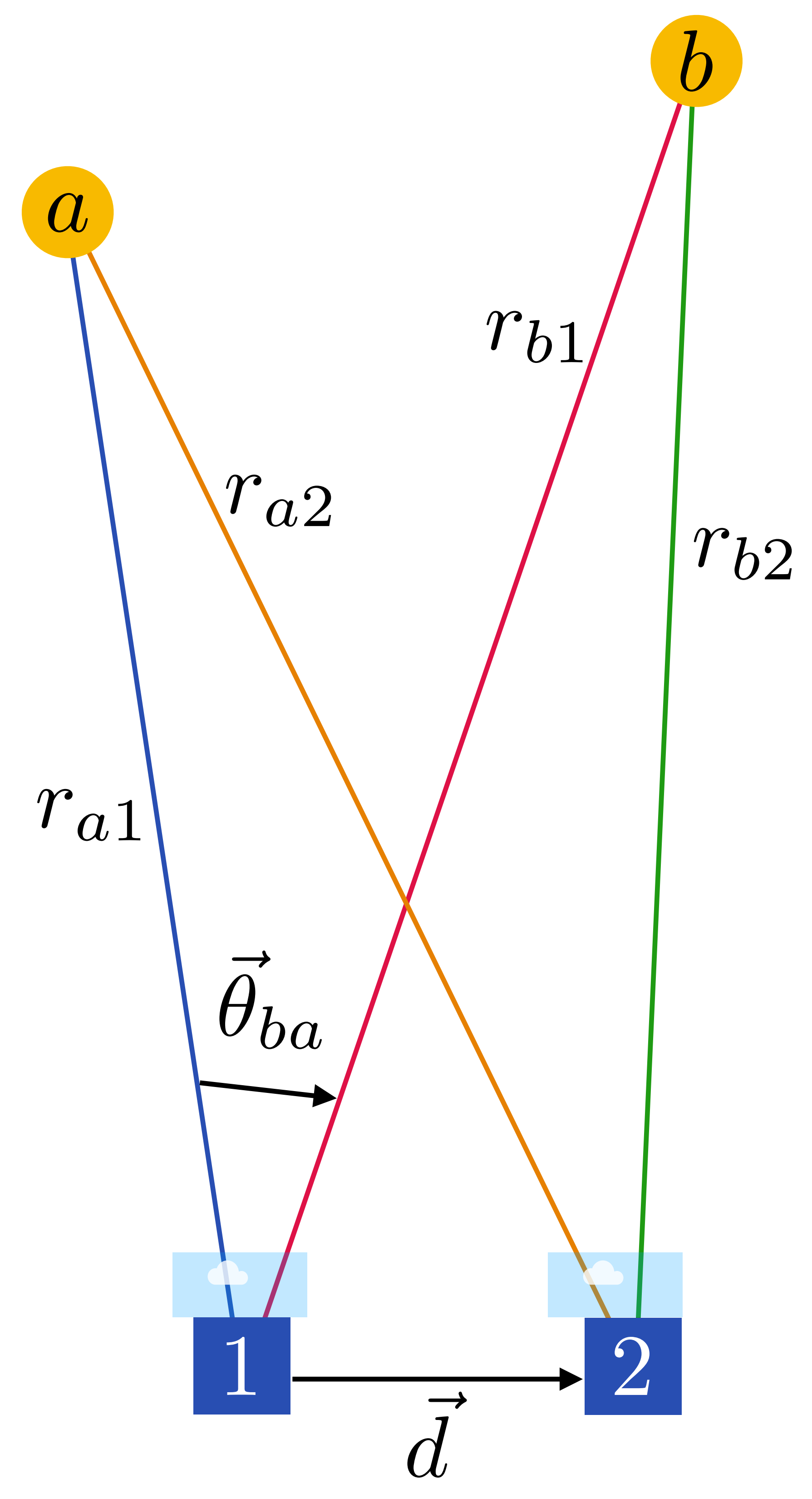


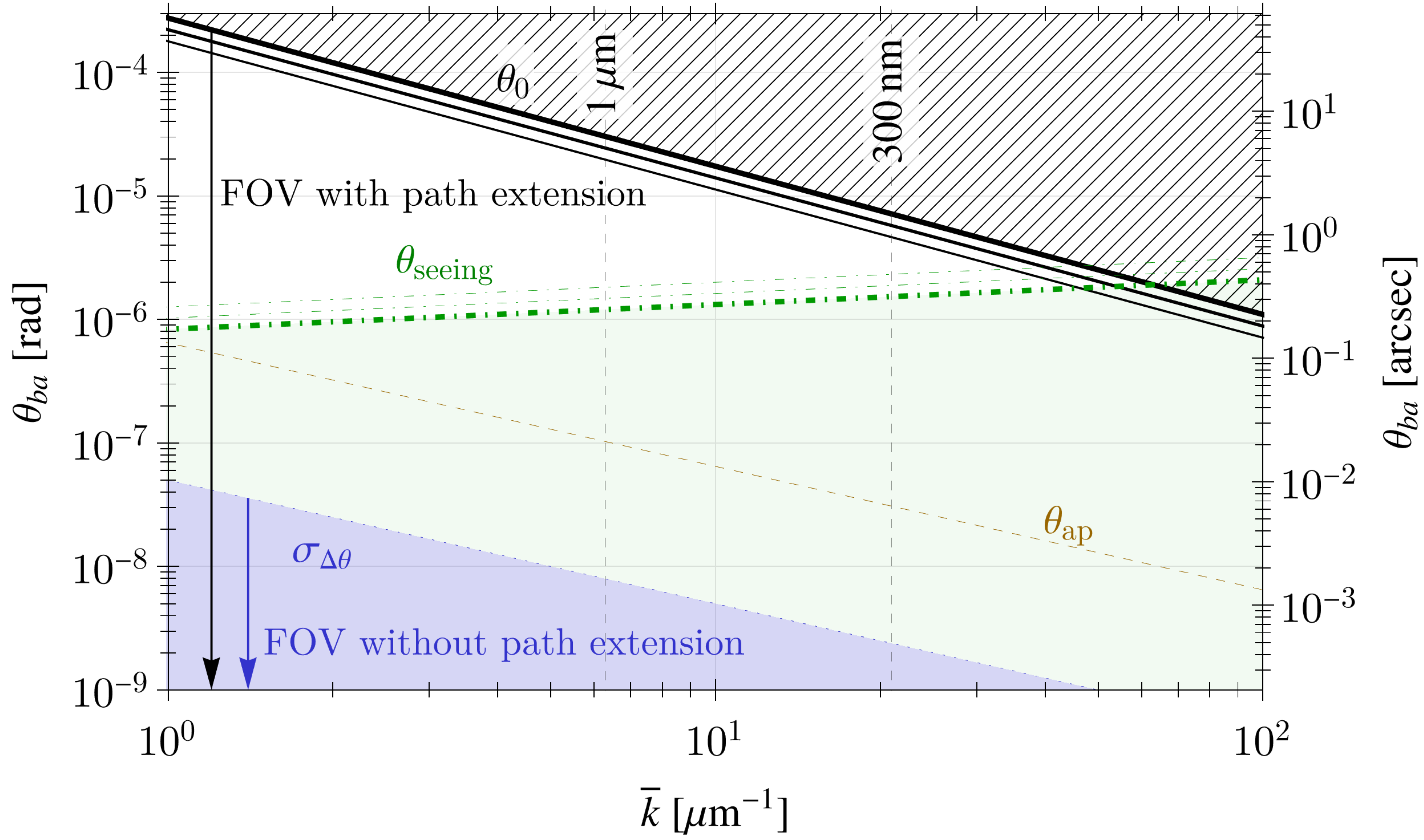
Atmospheric Aberrations





Atmospheric Aberrations





Outline

1. Introduction to Astrometry

- eye balls and imaging telescopes
- spectrographs
- amplitude interferometers

2. Intensity Interferometry

- basic idea
- extended path invention
- projected performance
- technical details

3. Scientific Applications

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

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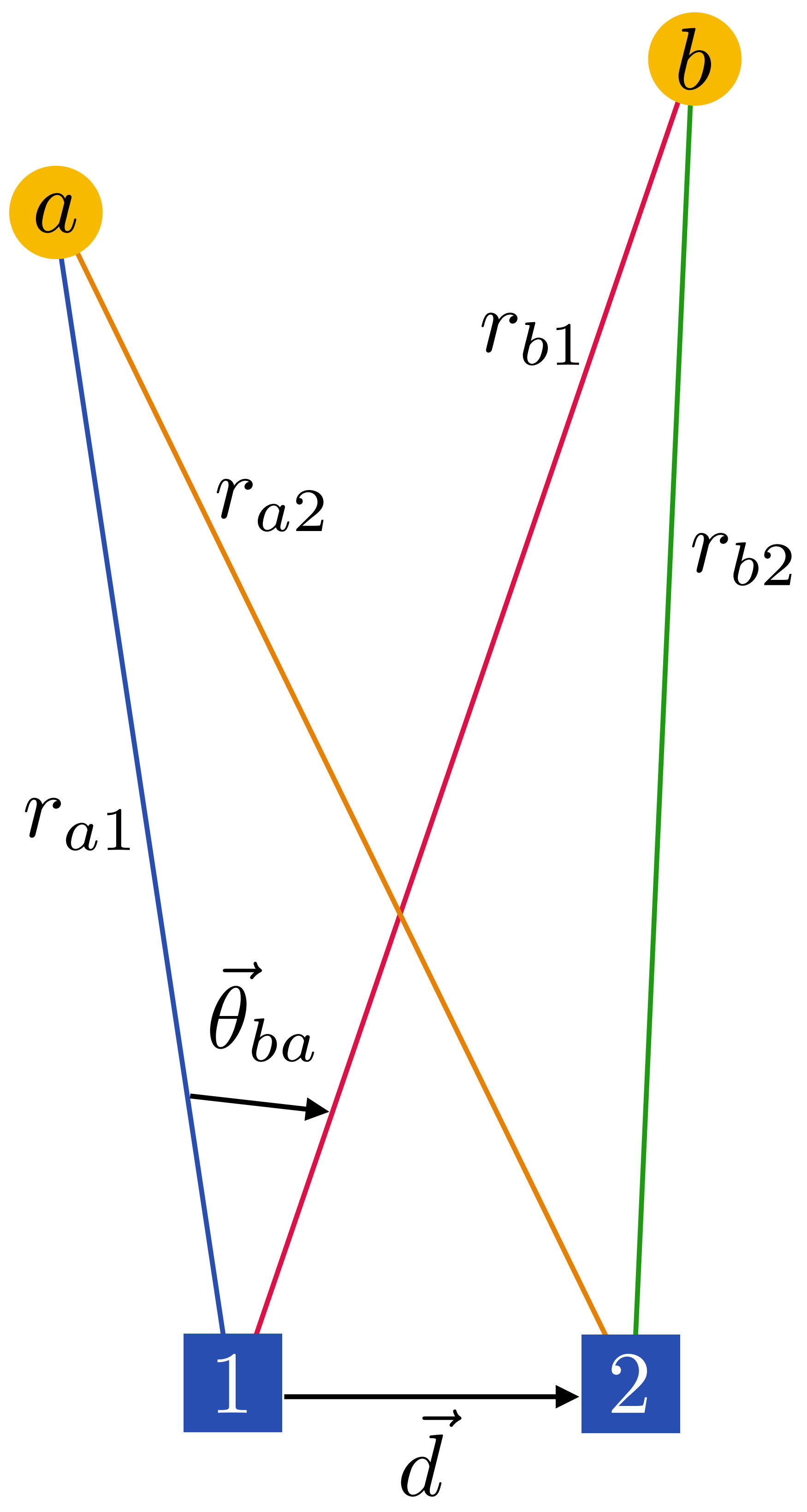
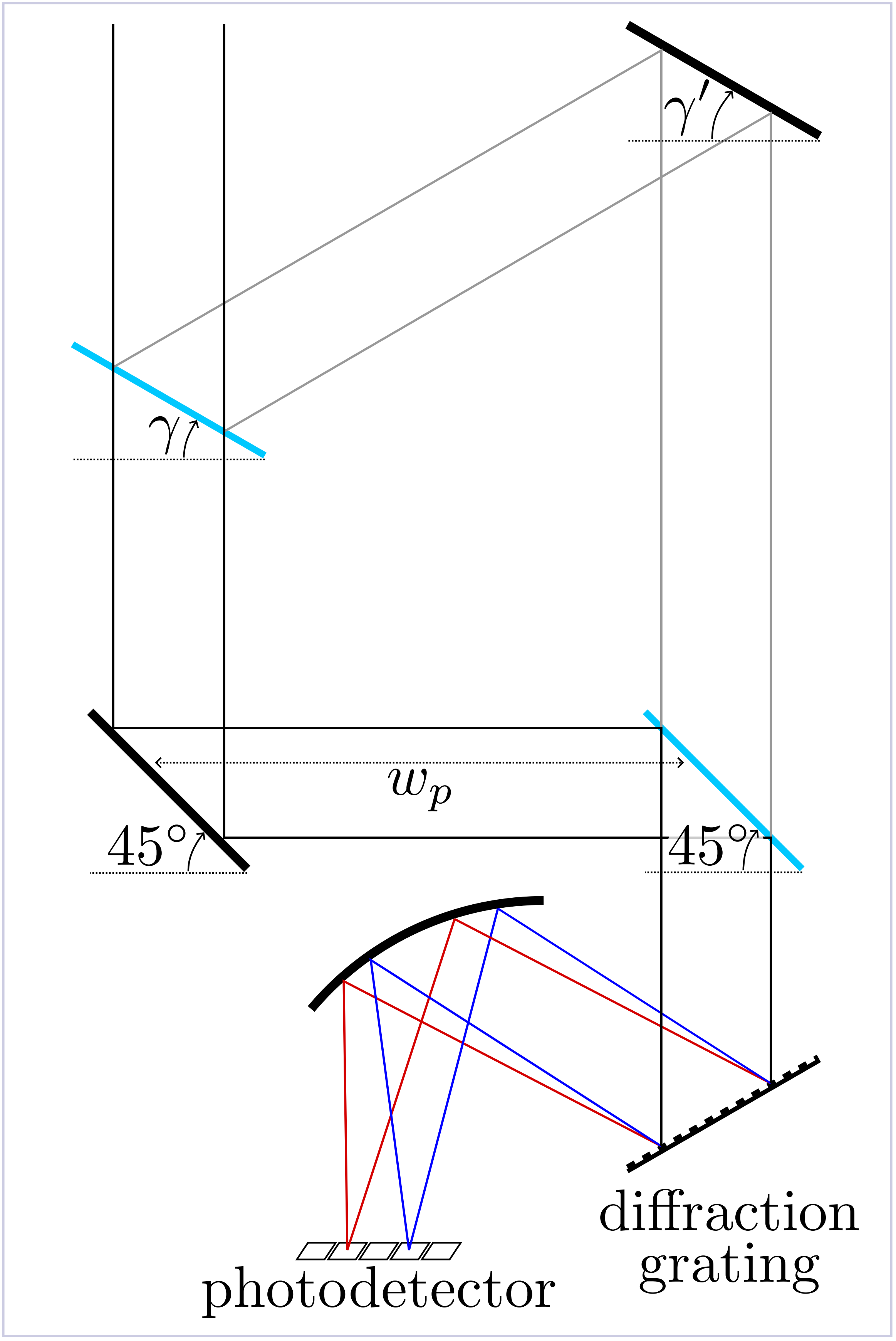
Scientific Applications

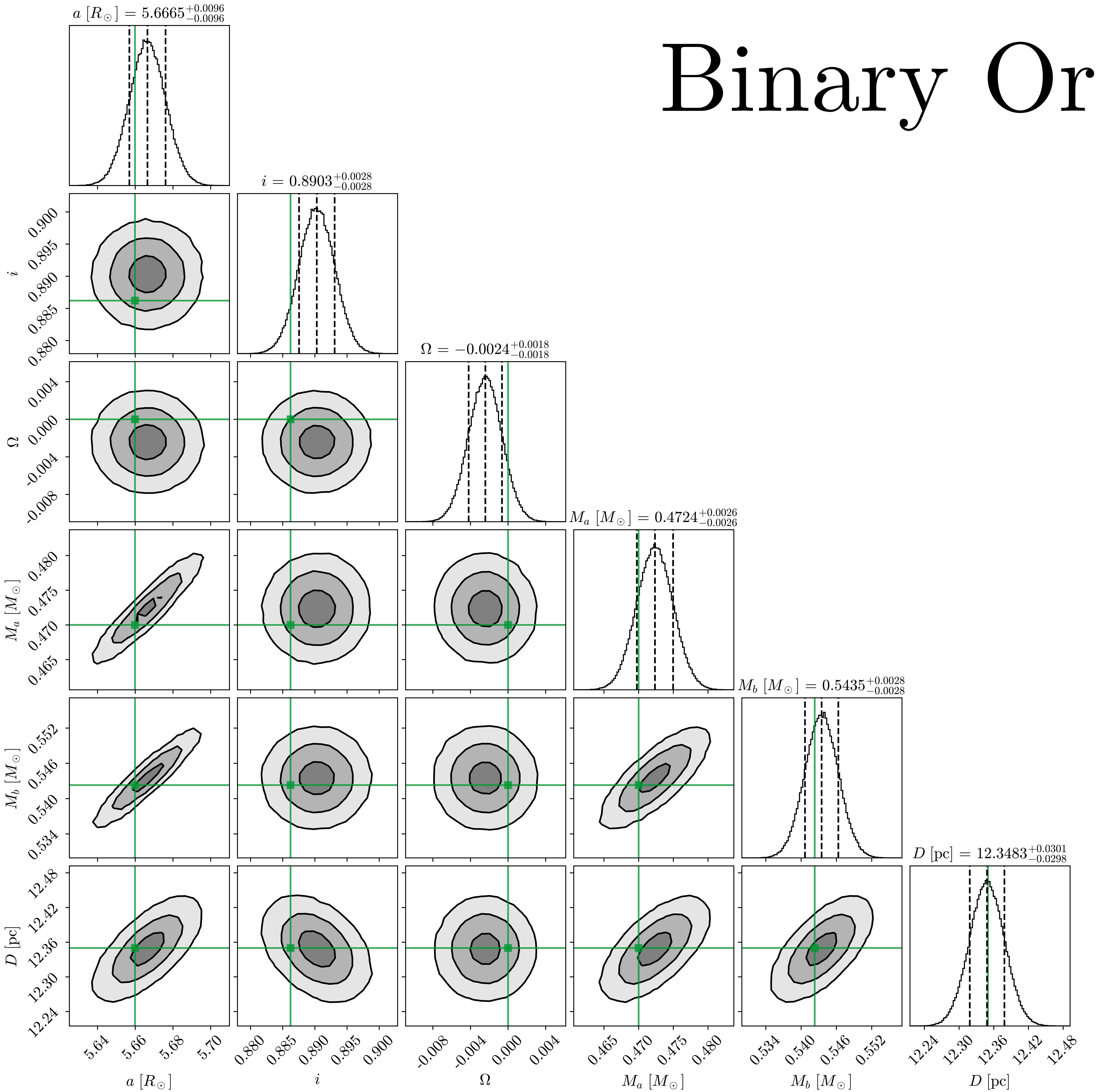
sub-μas resolution and even better *differential* light-centroiding precision

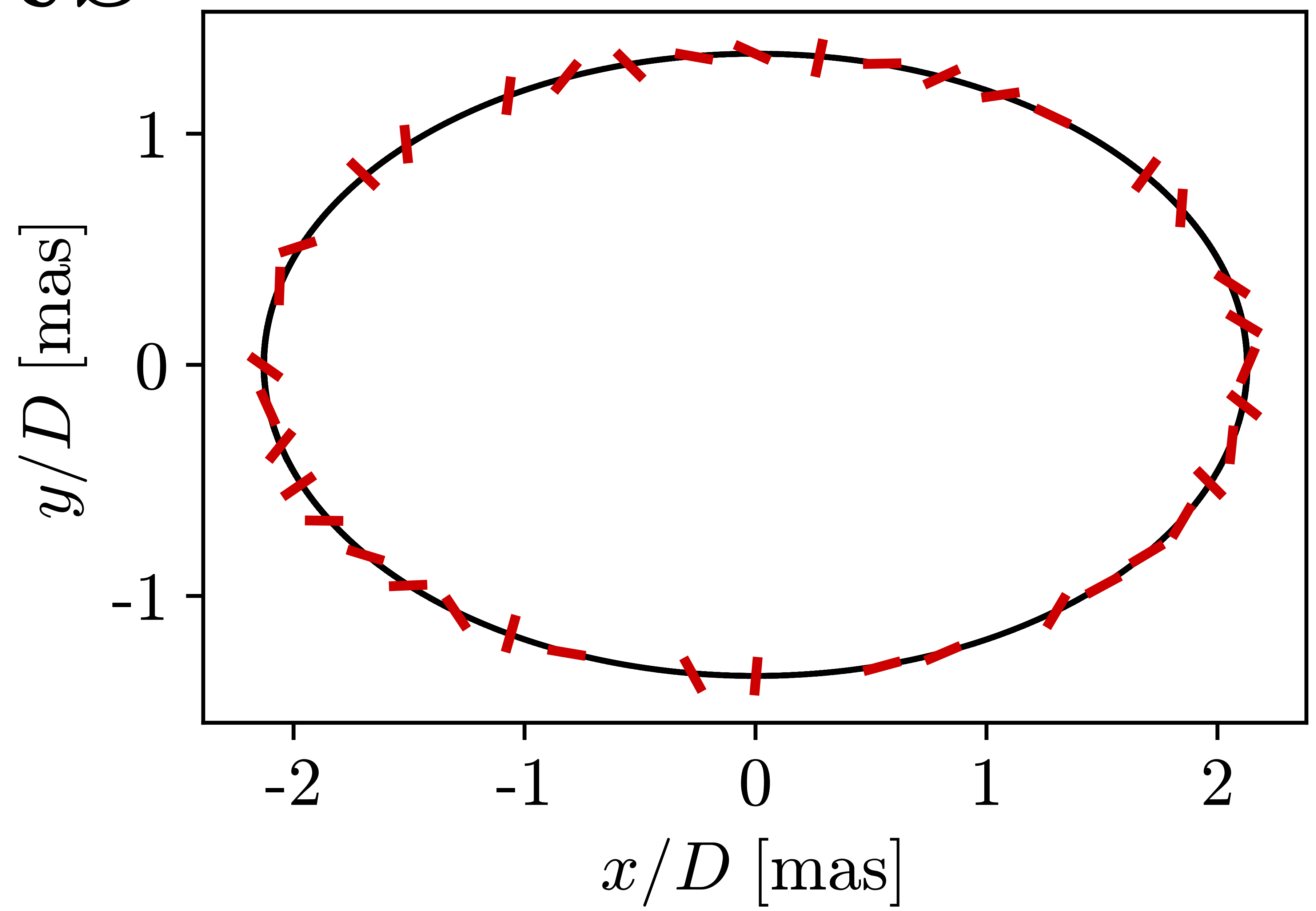
on sources separated by less than a few arcseconds

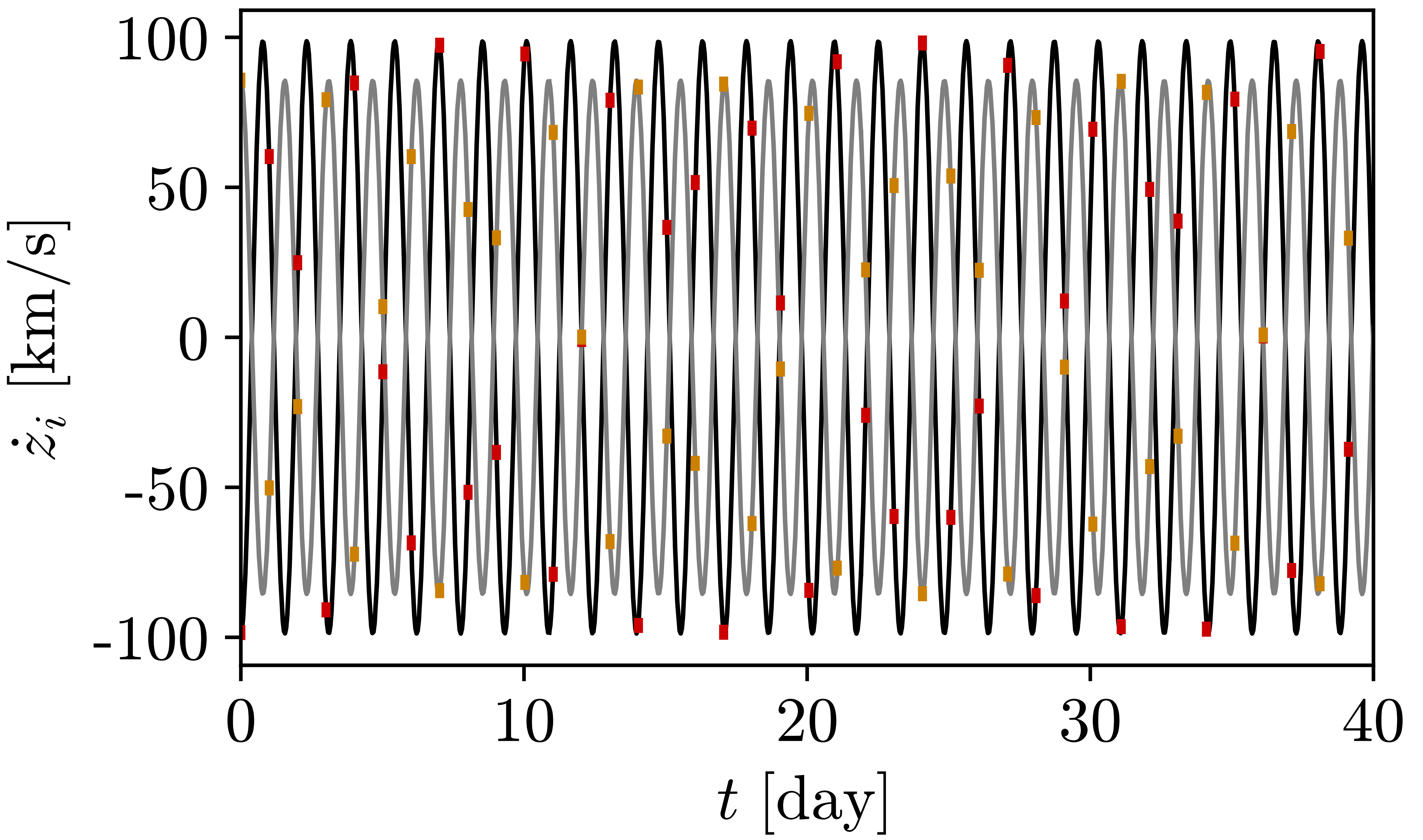




Binary Orbits







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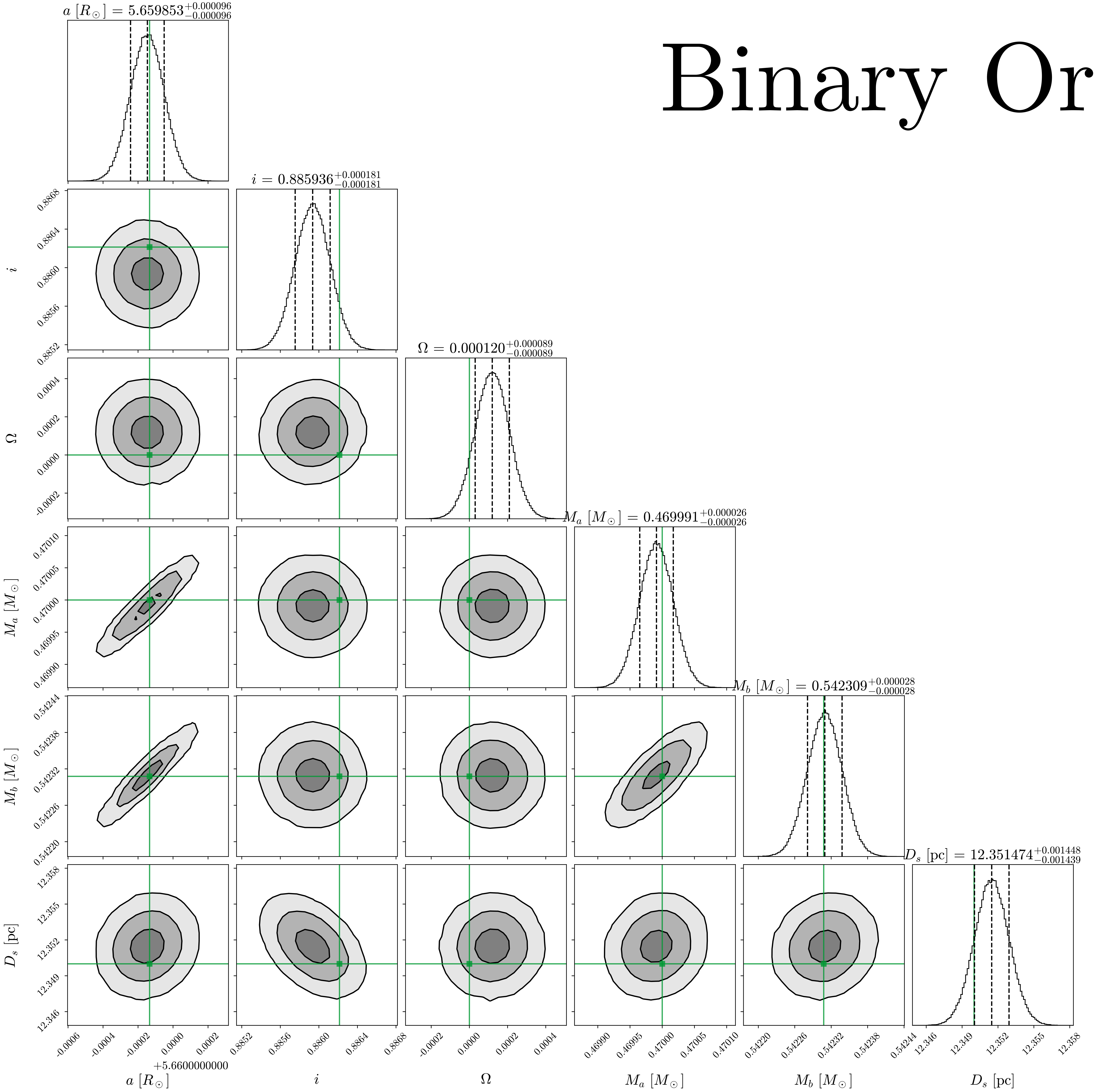
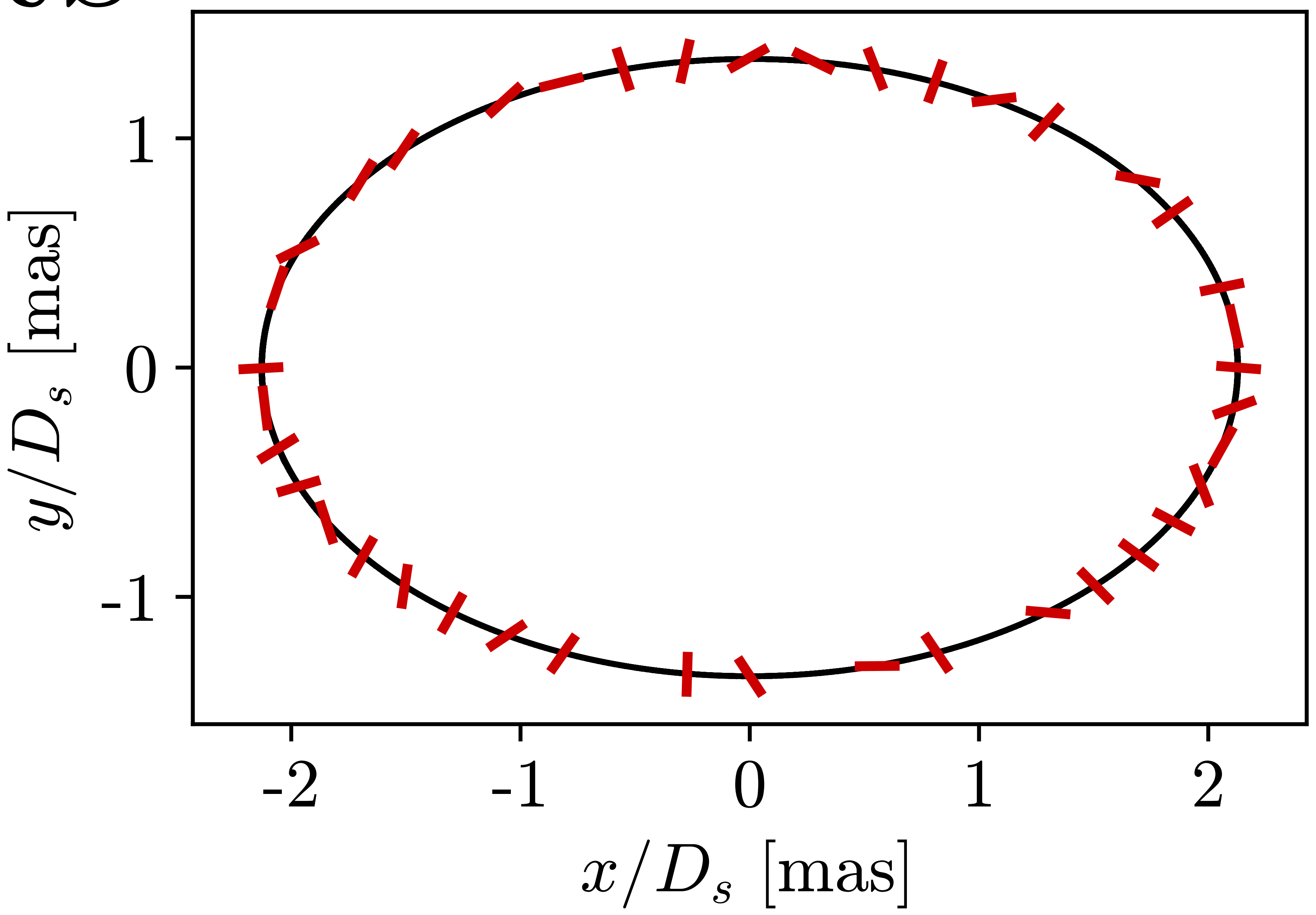
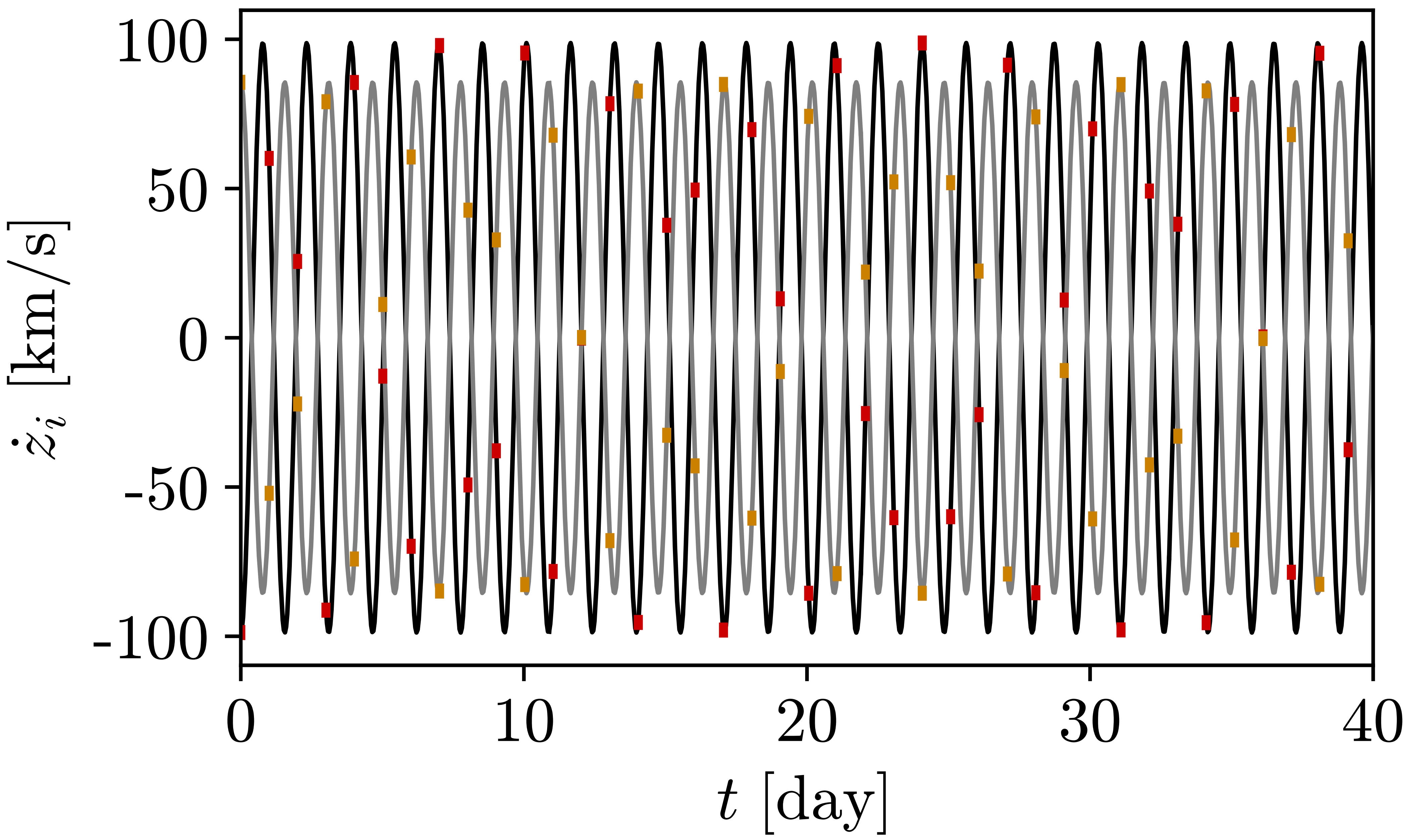
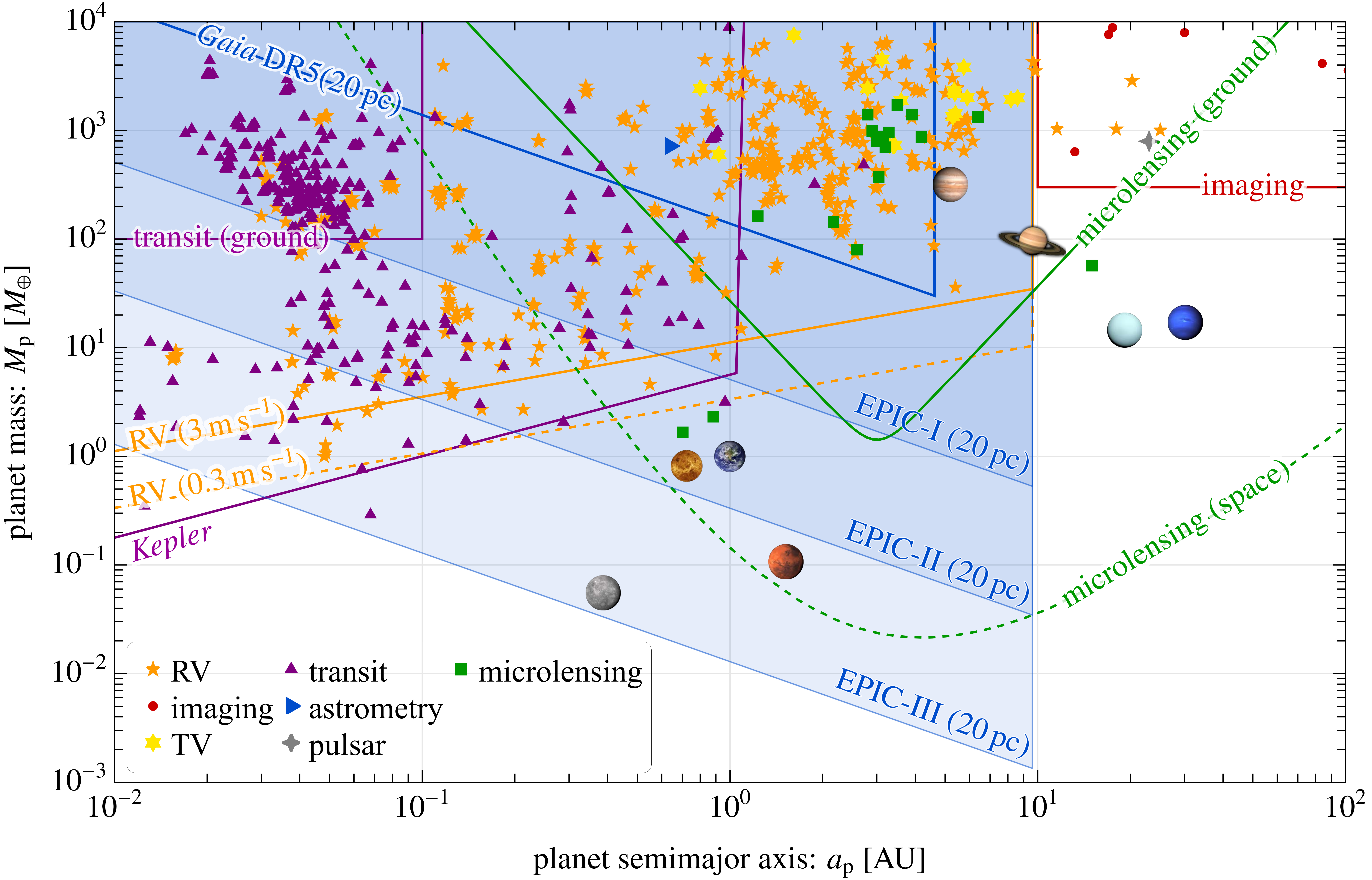




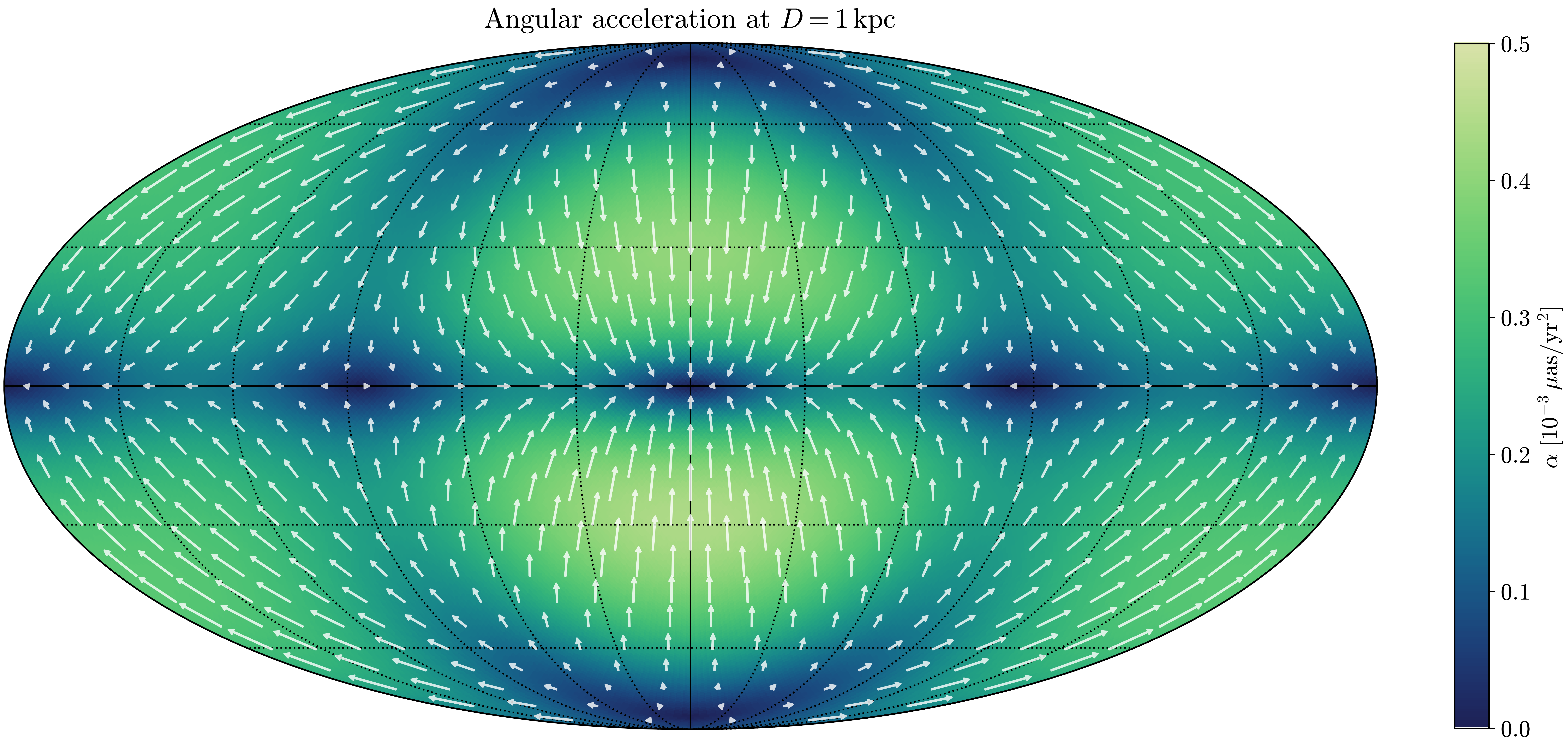


Exoplanets

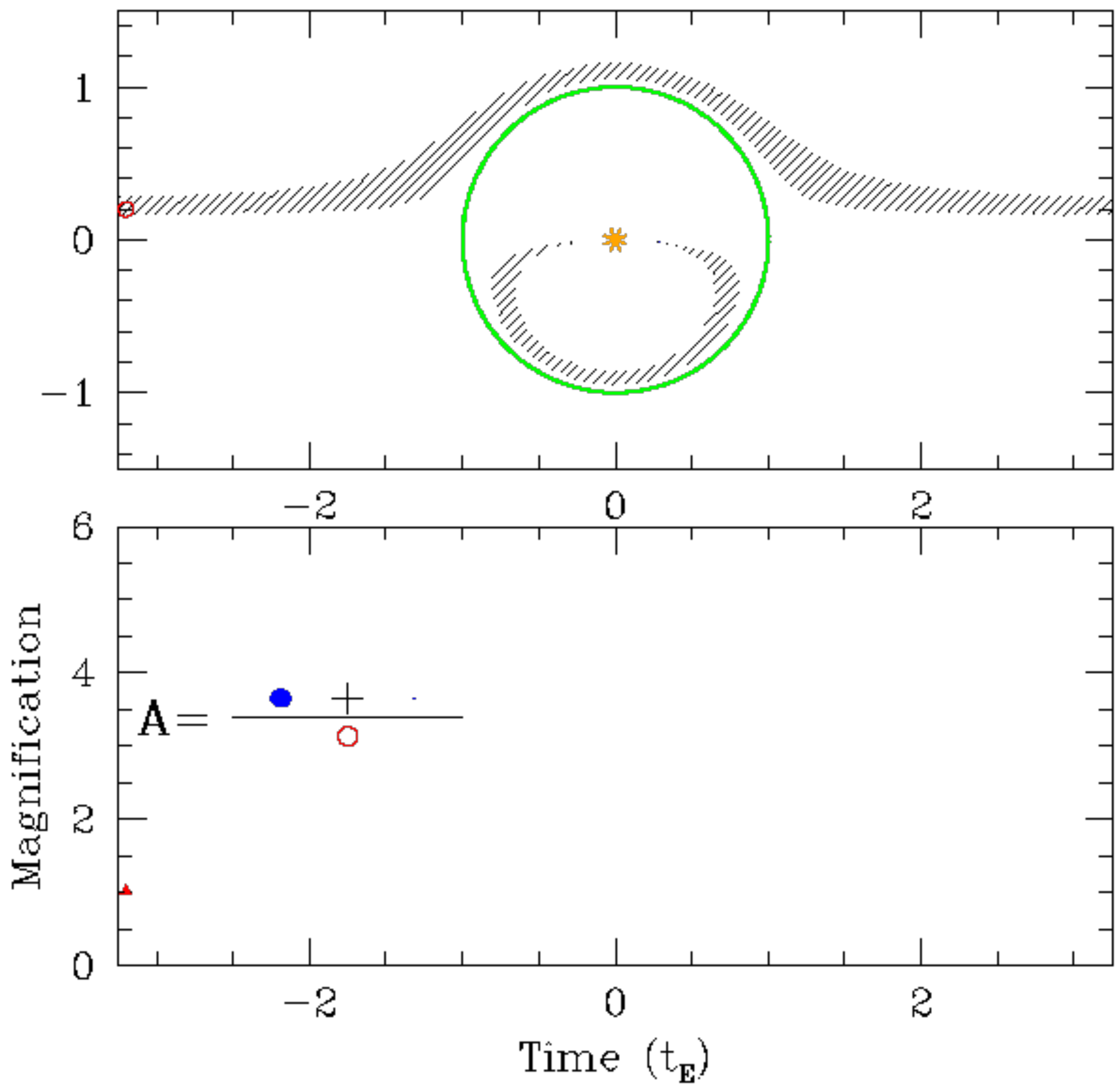
$$\Delta\theta_{\rm star} \sim \frac{M_{\rm p}}{M_{\rm star}} \frac{a_{\rm p}}{D}$$



Galactic Acceleration



Stellar Microlensing



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

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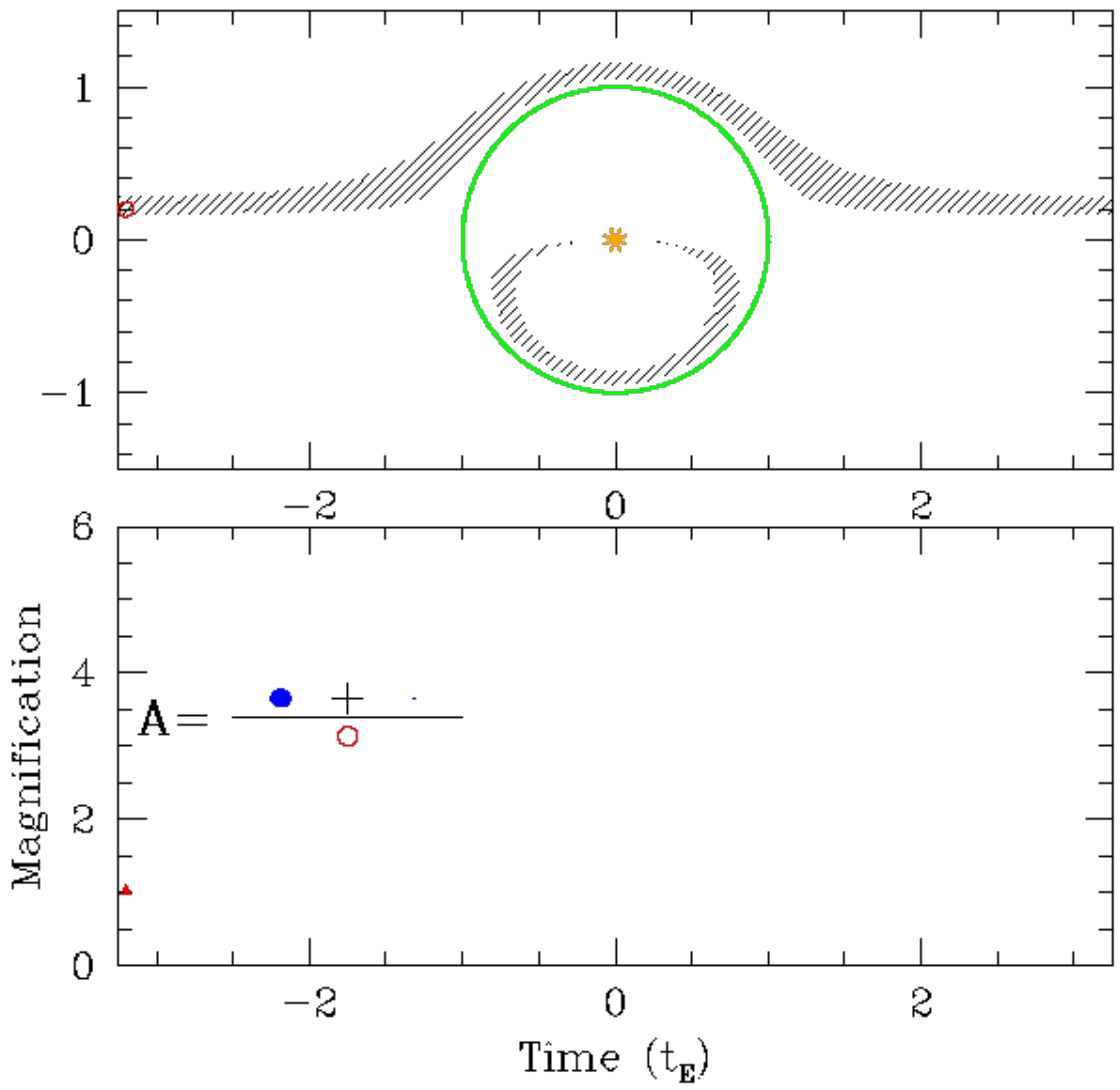

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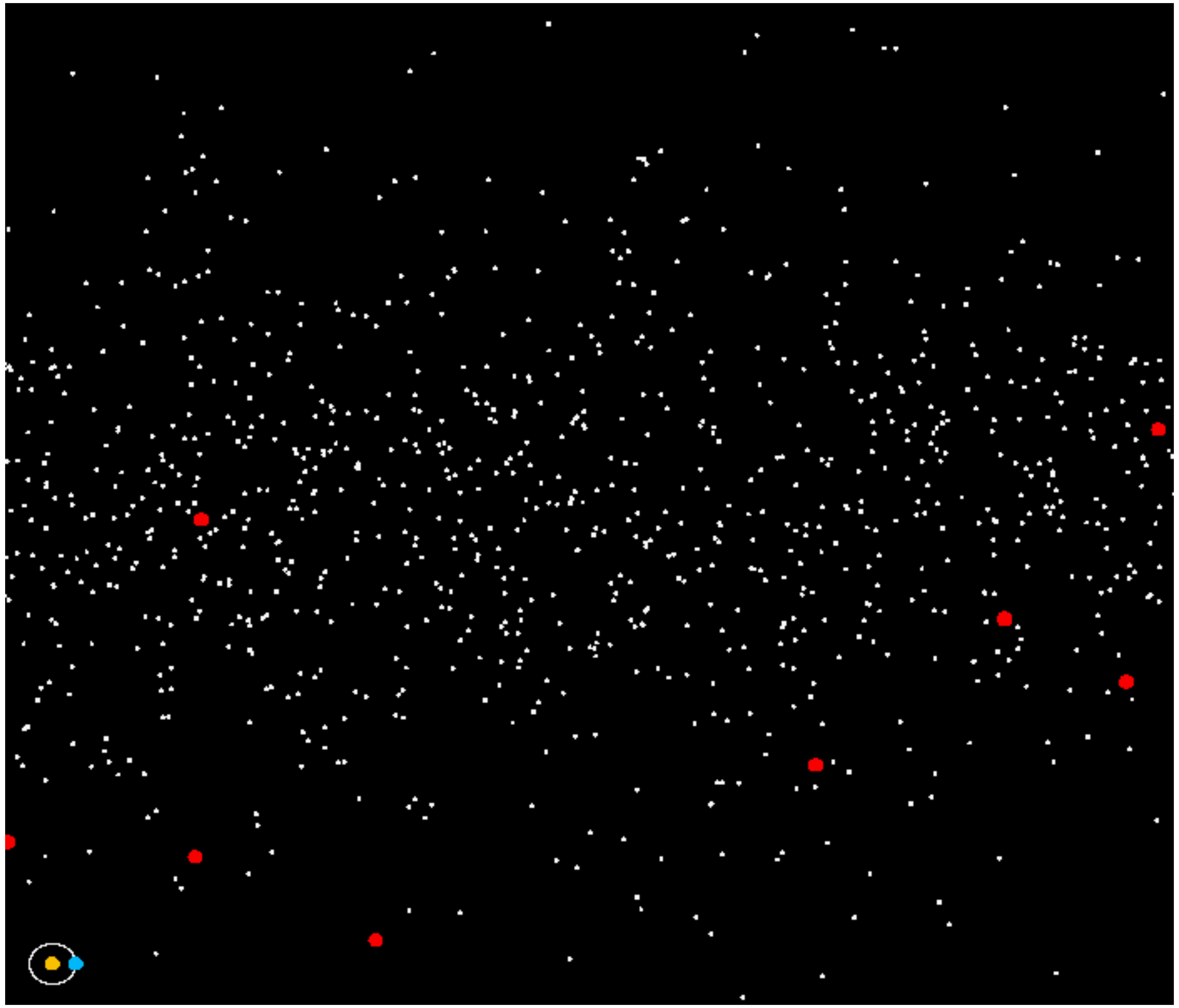
Cosmic Distance Ladder



$$\varpi_S \equiv 10\,\mu\mathrm{as}\frac{100\,\mathrm{kpc}}{D_S}$$

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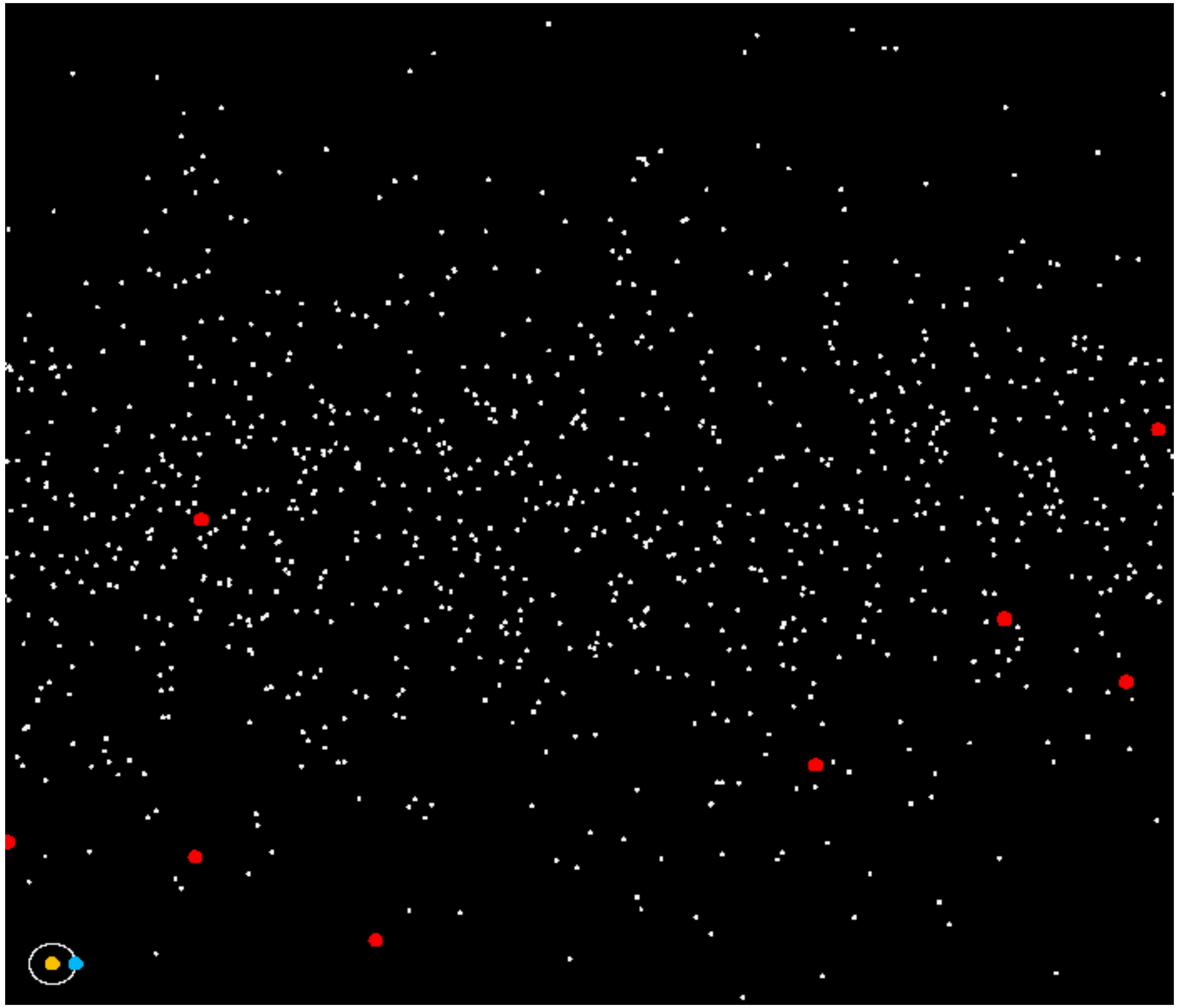

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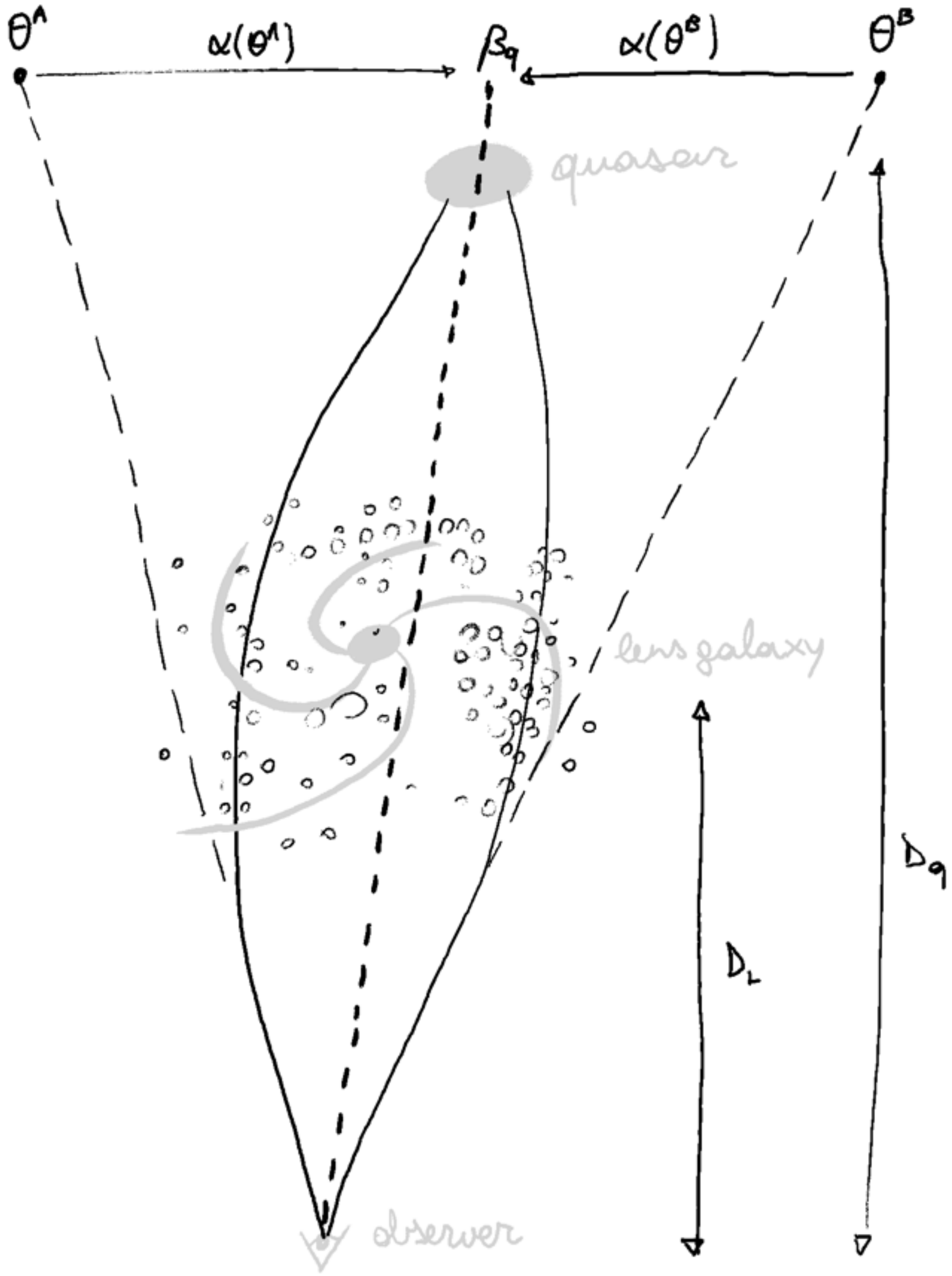
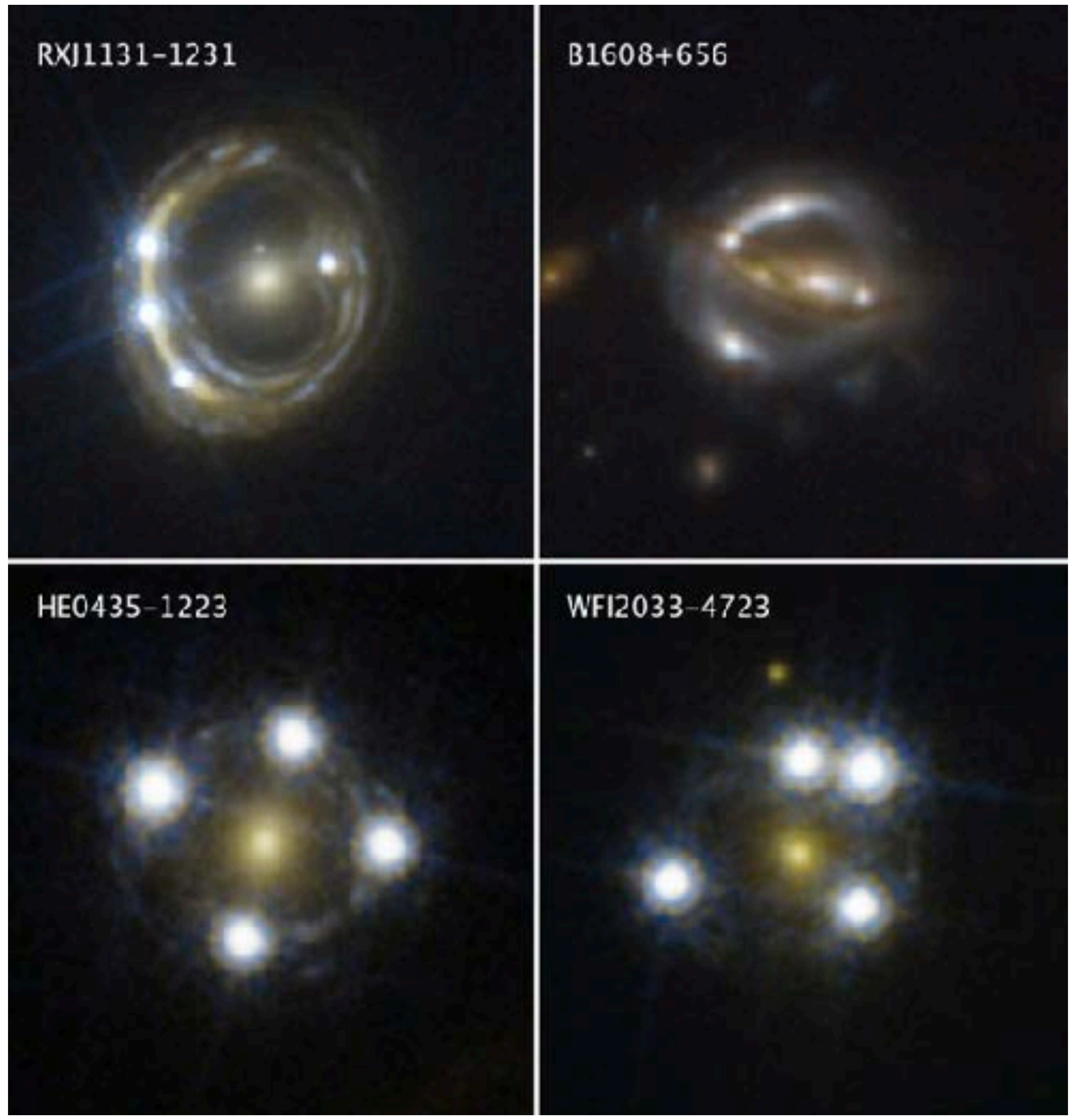
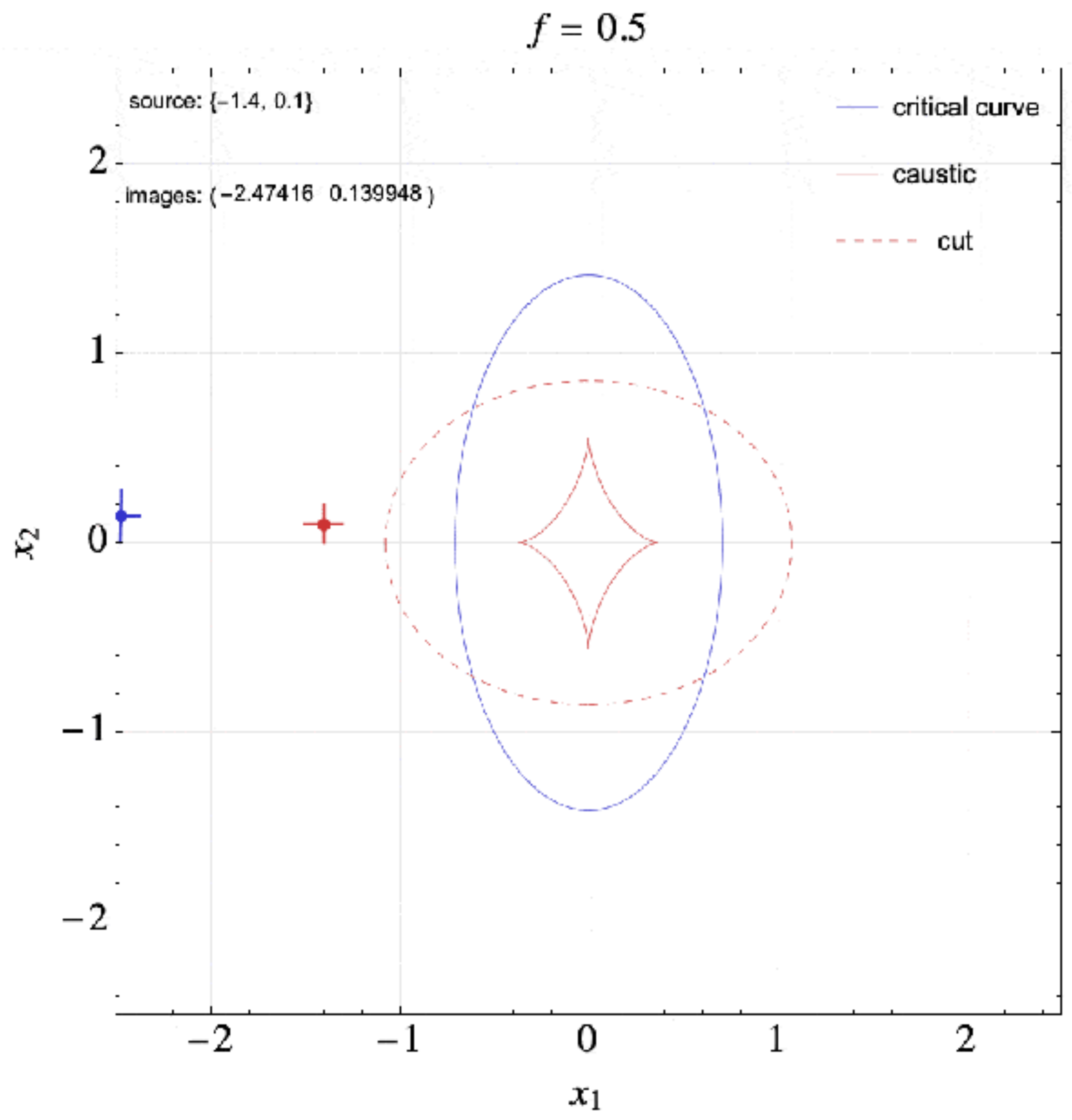
Quasar Microlensing

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: $\delta\theta^{\rm I} \sim B^{\rm I}\theta_E\sqrt{\kappa_L}$

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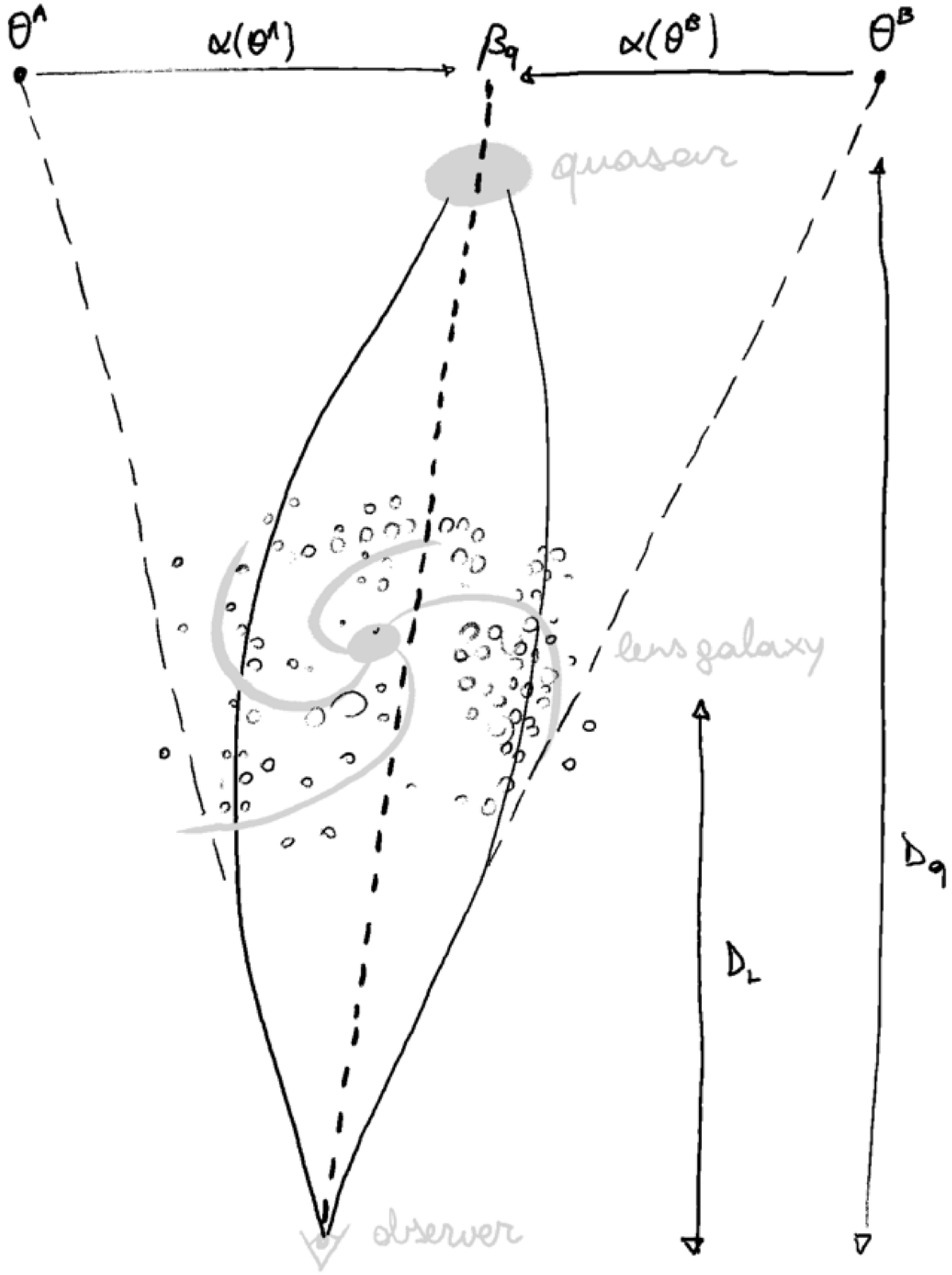

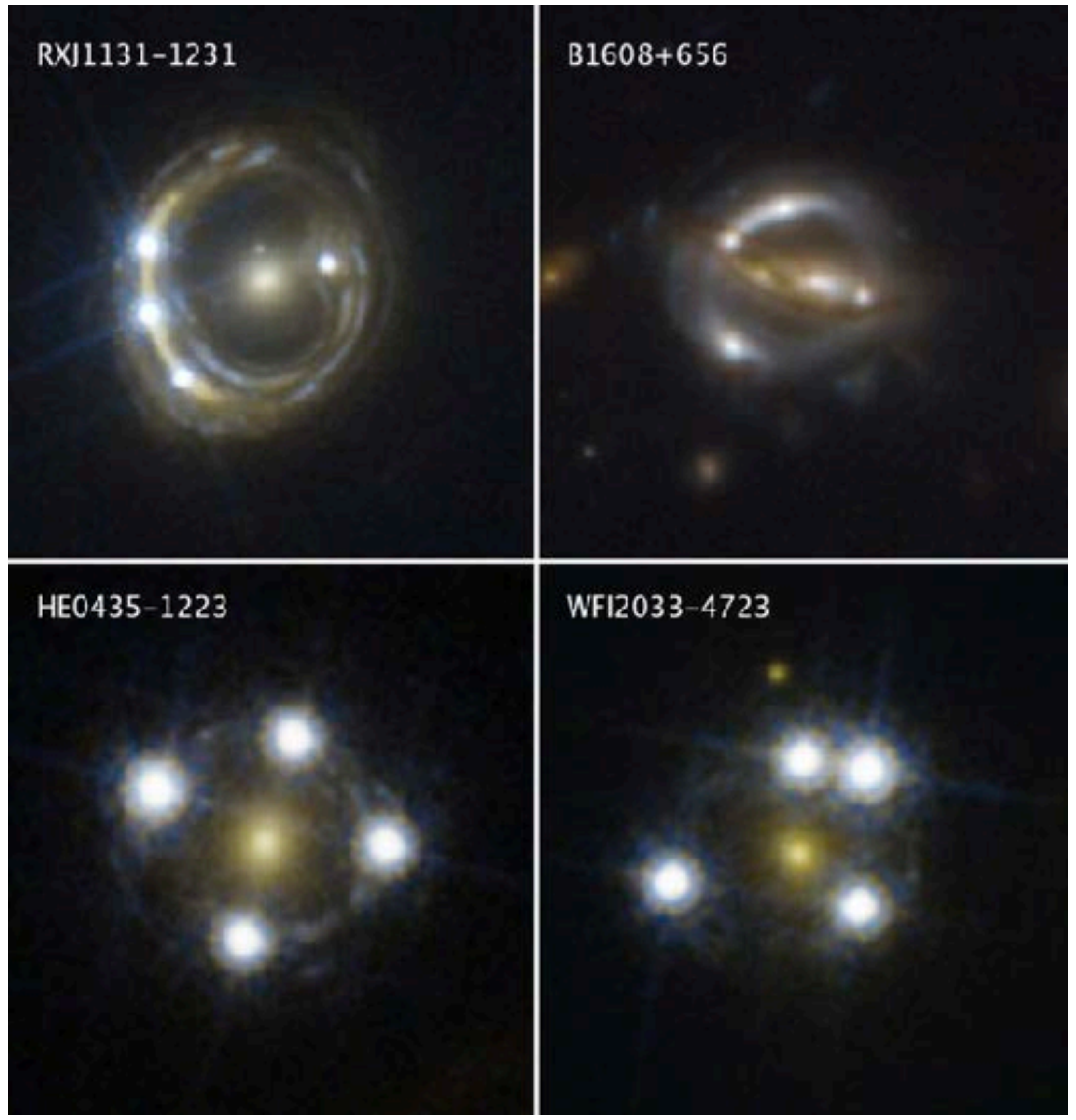

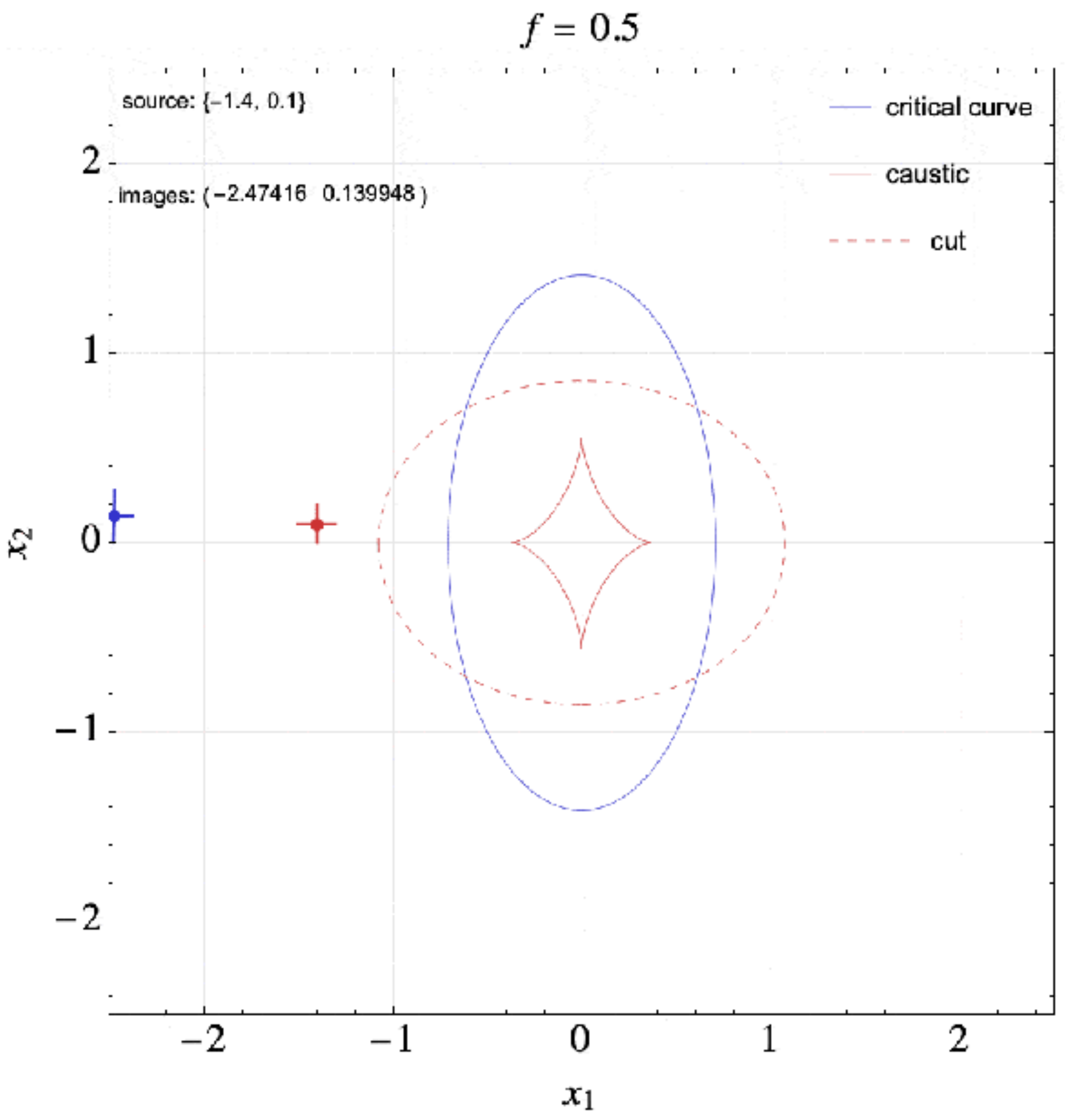

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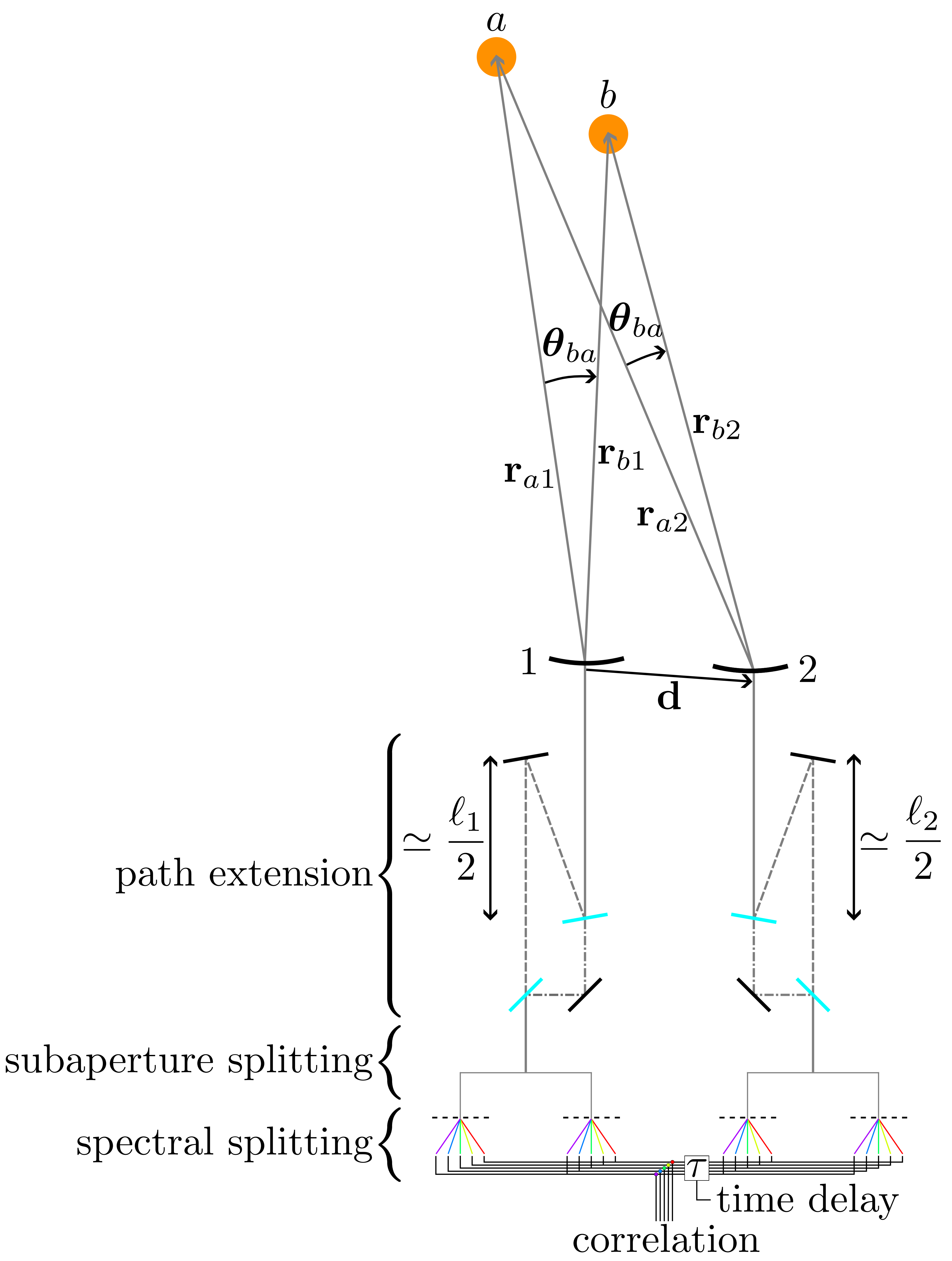

Conclusions

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

on sources separated by less than a few arcseconds

new astrophysical applications

expansion rate of the Universe

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*