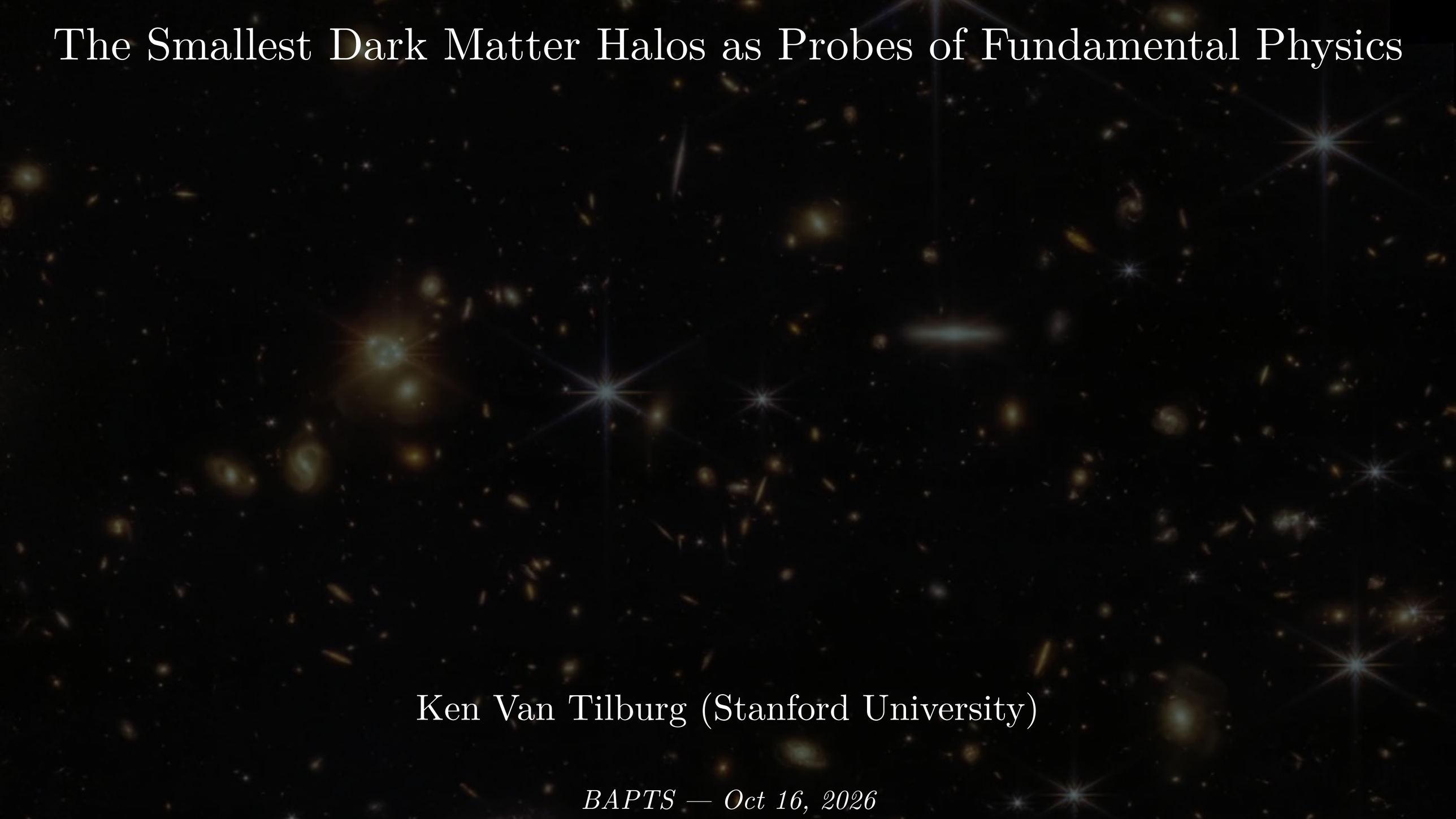
The Smallest Dark Matter Halos as Probes of Fundamental Physics

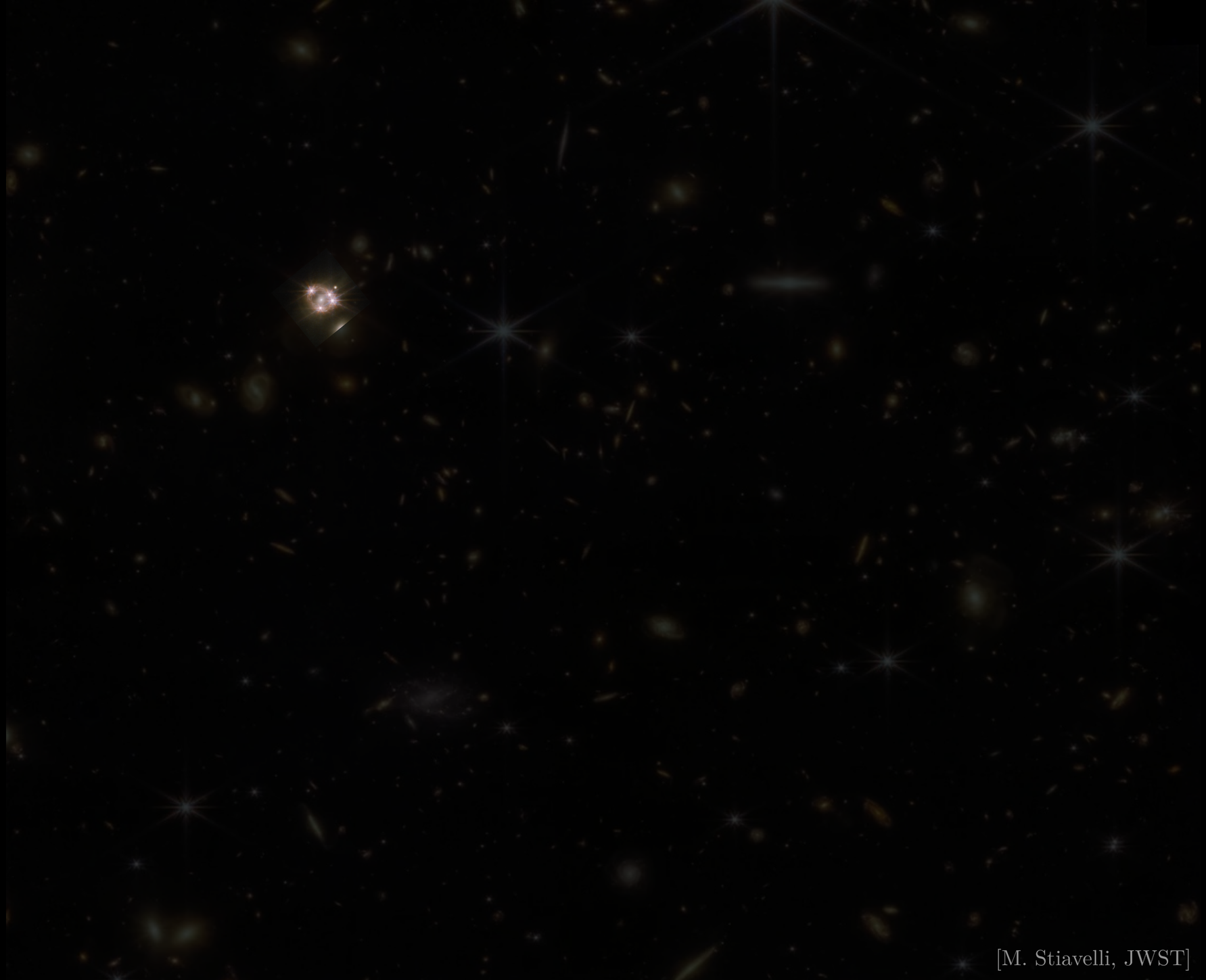


Ken Van Tilburg (Stanford University)

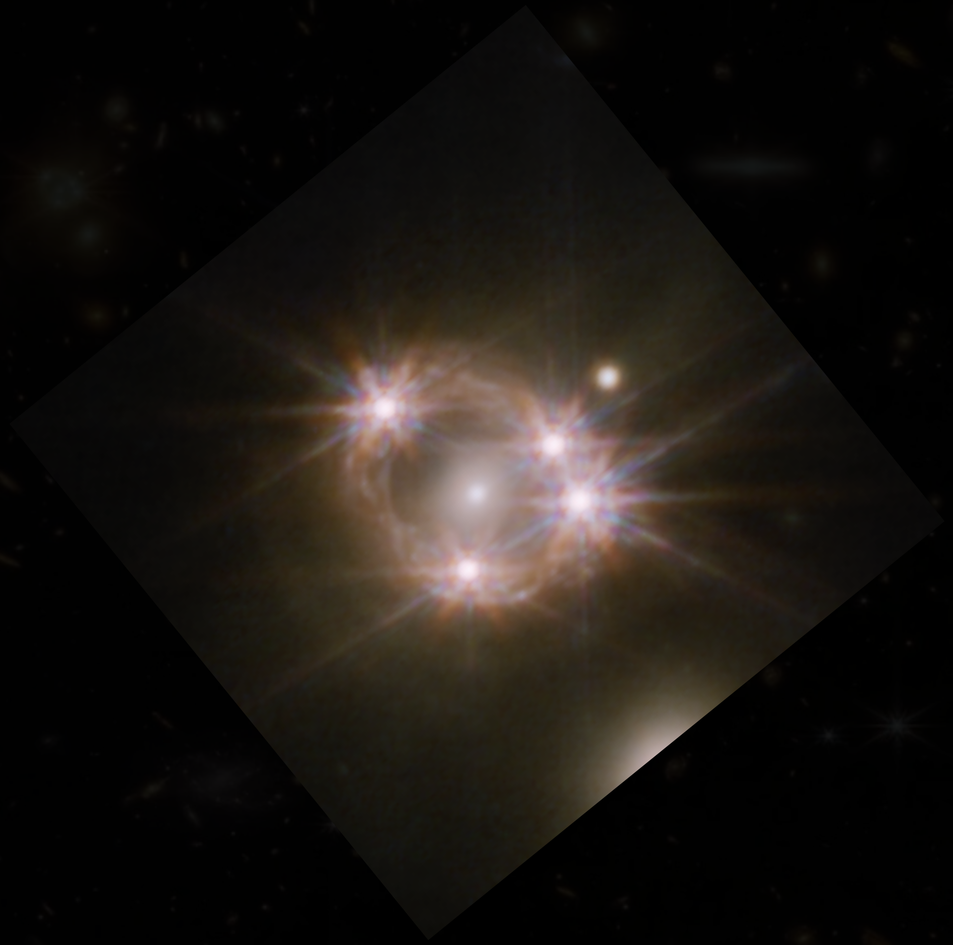
BAPTS — Oct 16, 2026



[M. Stiavelli, JWST]



[M. Stiavelli, JWST]



How noisy is spacetime?

How noisy is spacetime?

(I don’t mean “loud”)

How noisy is spacetime?

(I don't mean "loud")

(Not a talk about quantum gravity)

How noisy is spacetime?

(I don't mean "loud") (Not a talk about quantum gravity) (I am not a crackpot)





[Michael Finsand]



[NASA *LRO*]



[Michael Finsand]



[NASA *LRO*]



[Michael Finsand]

How noisy is the atmosphere?





[NASA *LRO*]

[Michael Finsand]

How noisy is spacetime? $\cong$ How noisy is the atmosphere?



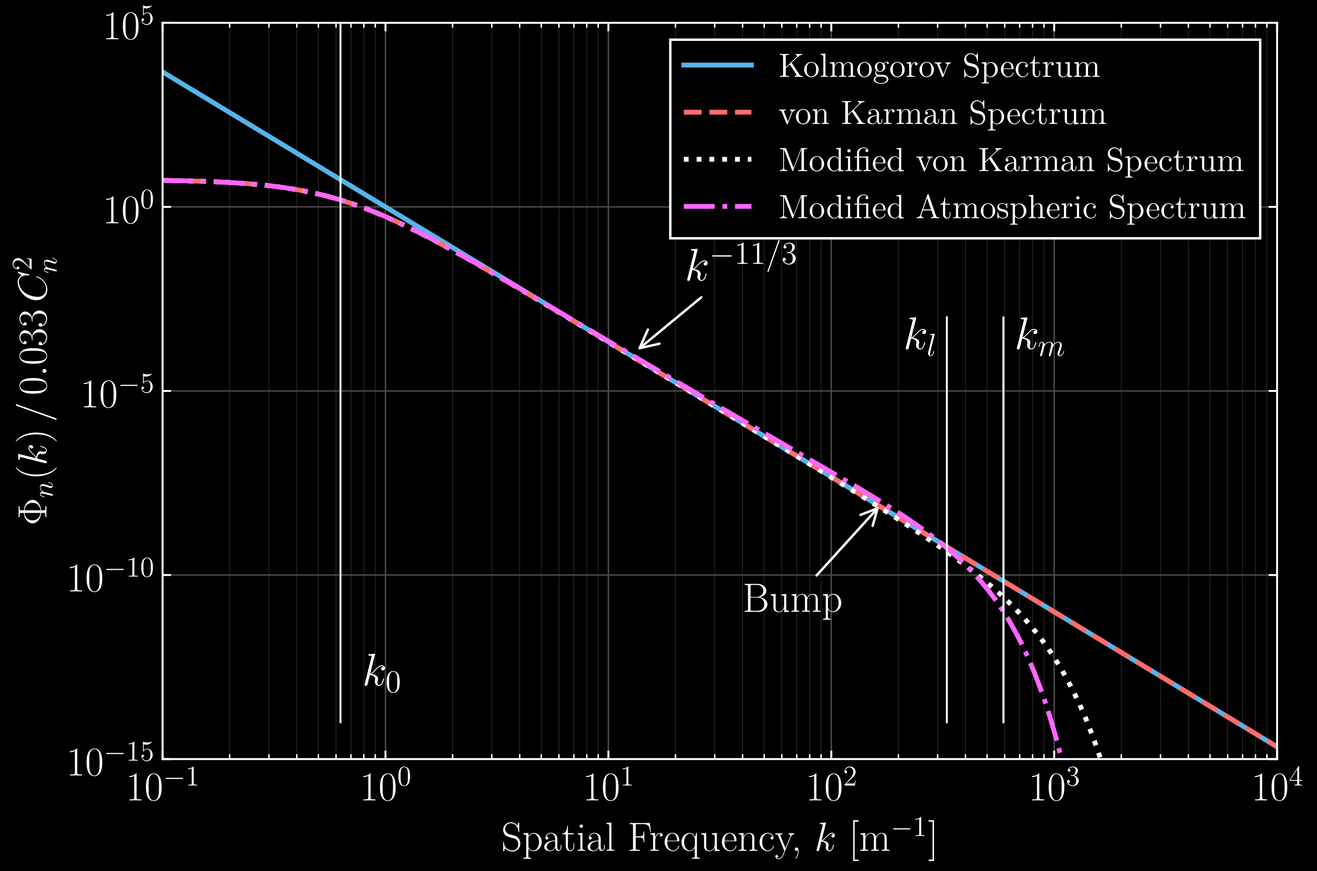


[NASA *LRO*]

[Michael Finsand]

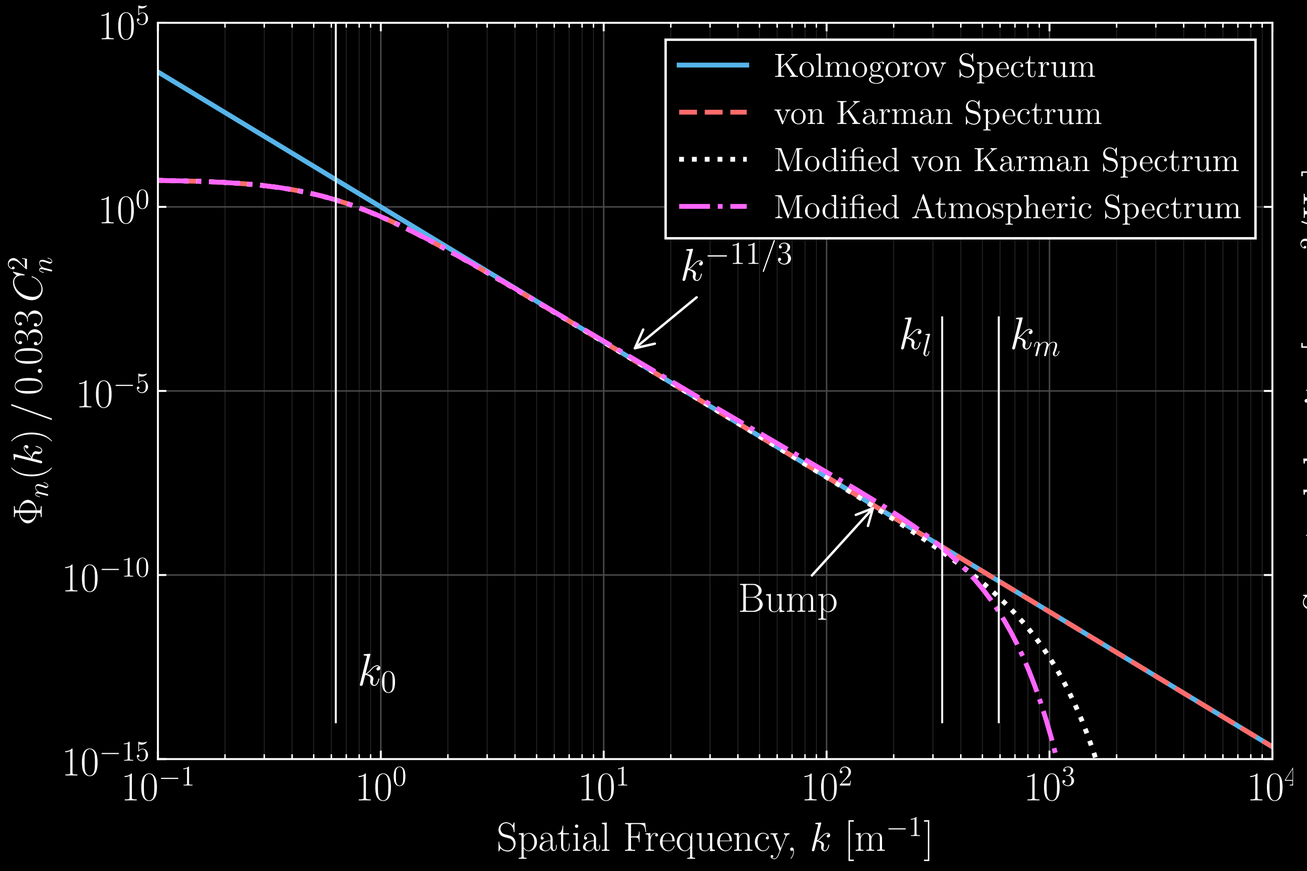
How noisy is the atmosphere?

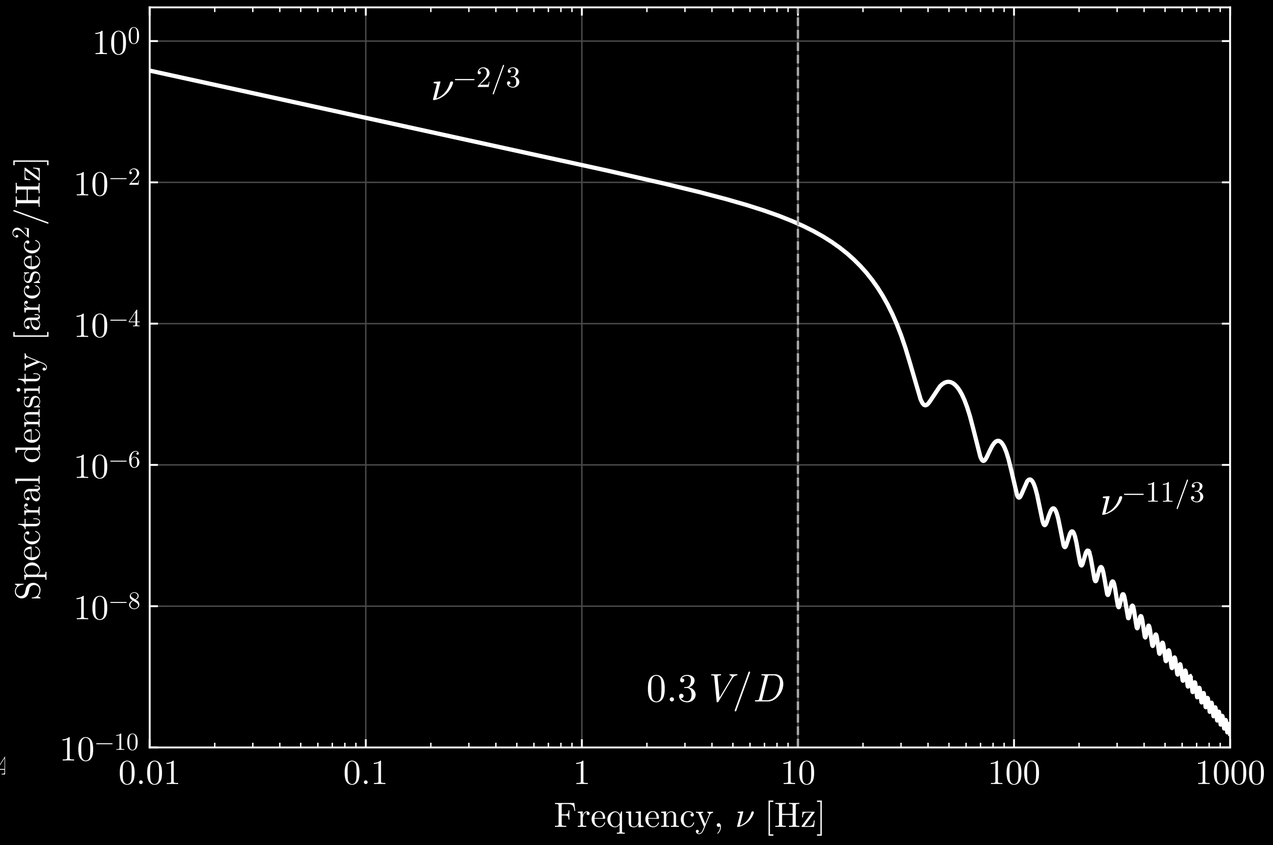
Turbulent density, temperature > fluctuating refractive index



How noisy is the atmosphere?

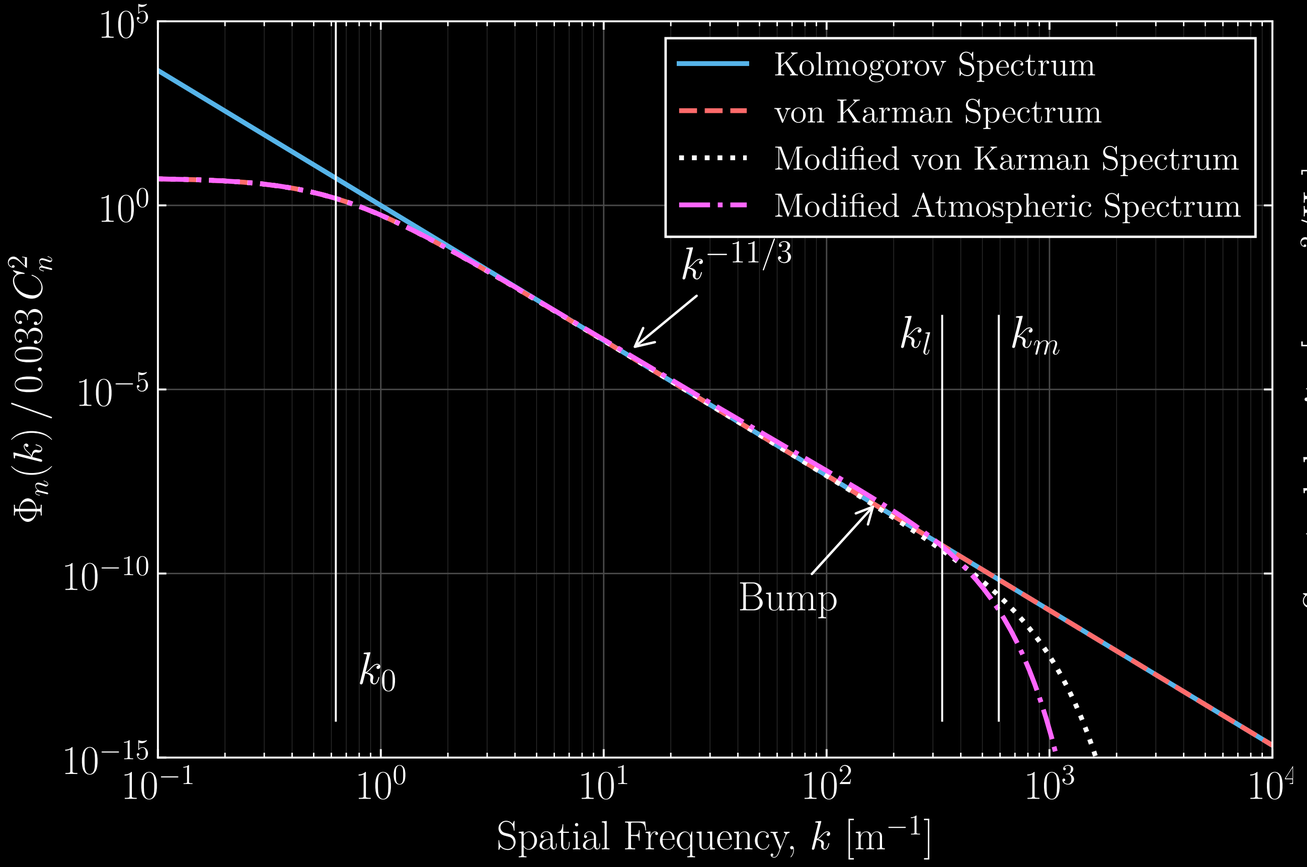
Turbulent density, temperature > fluctuating refractive index > time-dependent deflections > astrometric noise

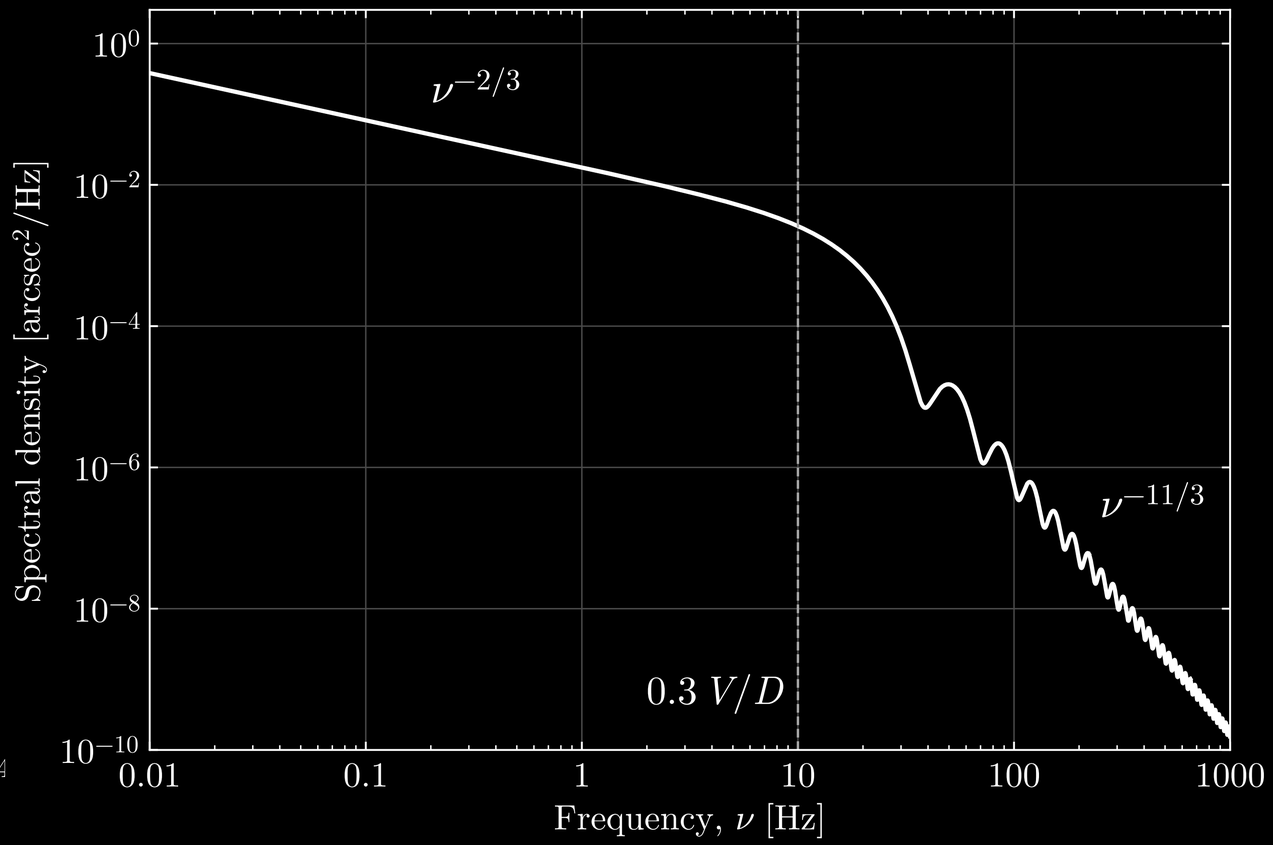




How noisy is the atmosphere?

Turbulent density, temperature > fluctuating refractive index > time-dependent deflections > astrometric noise





How noisy is spacetime?

Matter fluctuations (halos) > fluctuating gravitational potential > time-dependent deflections > astrometric noise

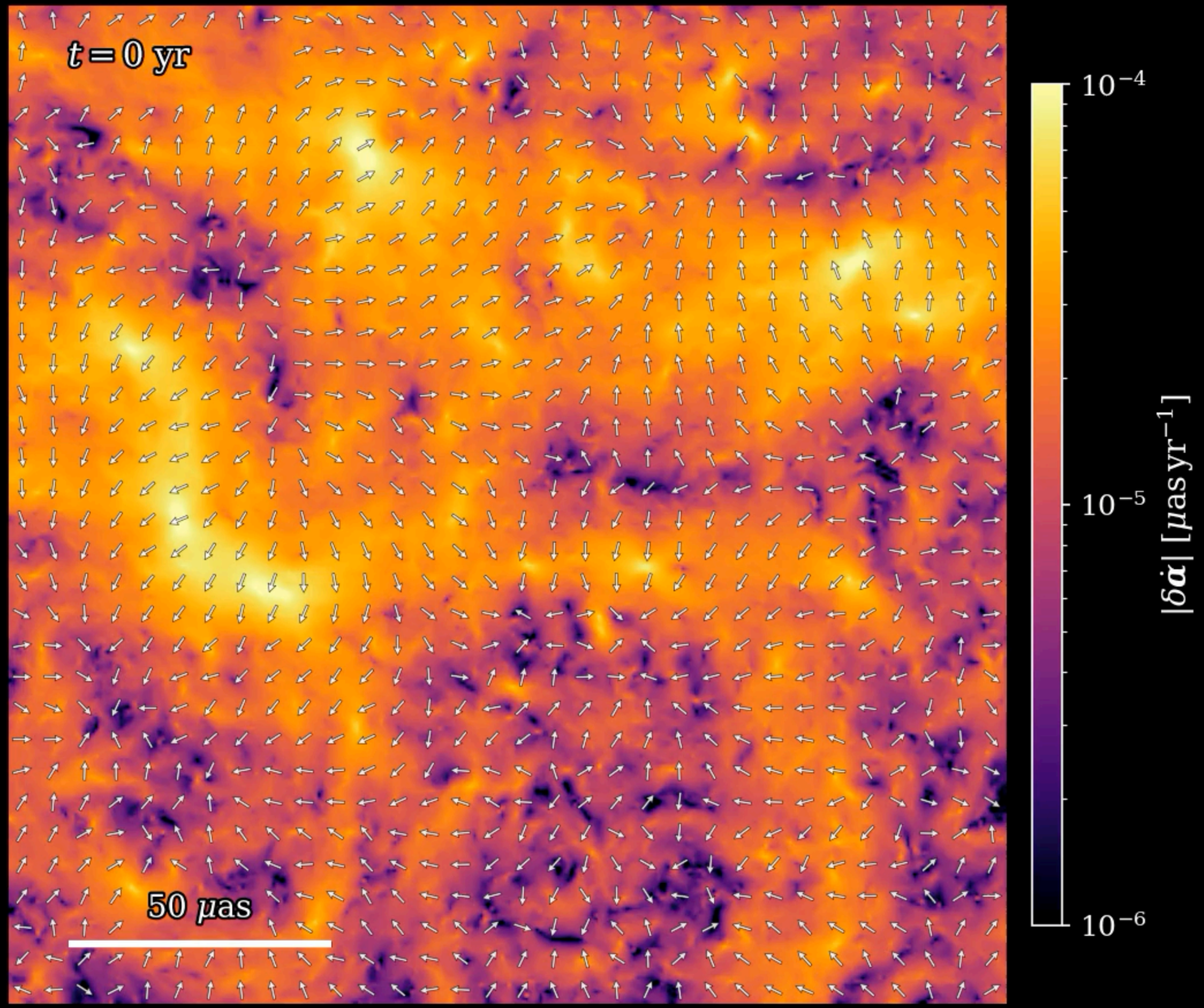
How noisy is spacetime?

How noisy is spacetime?

(along generic line of sight)

How noisy is spacetime?

(along generic line of sight)



Outline

1. Motivation
2. Signature
3. Sensitivity Forecast
4. Existing Data
5. Future Data

Outline

0

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2. Signature

3. Sensitivity Forecast

4. Existing Data

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"Halometry from Astrometry"

[KVT, A.-M. Taki, N. Weiner; arXiv:1804.01991]

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"Halometry from Astrometry"

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[C. Mondino, A.-M. Taki, KVT, N. Weiner; 2002.01938]

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[I.-K. Chen, M. Kongsore, KVT; 2306.13137]

[C. Mondino, A. Tsantilas, A.-M. Taki, KVT, N. Weiner; 2308.12330]

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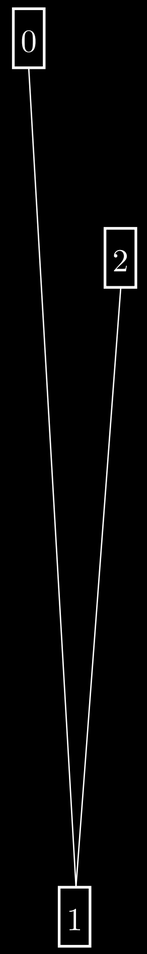
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5. Future Data

[KVT, M. Baryakhtar, M. Galanis, N. Weiner; arXiv:2307.03221]

[M. Galanis, KVT, M. Baryakhtar, N. Weiner; arXiv:2307.06989]

Outline



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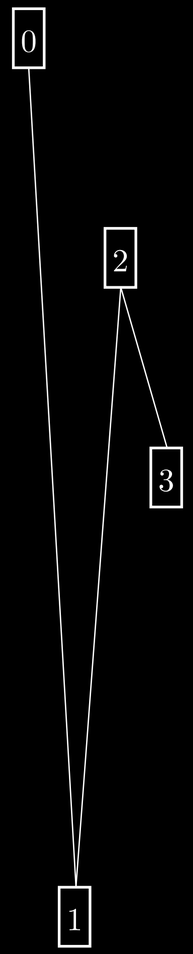
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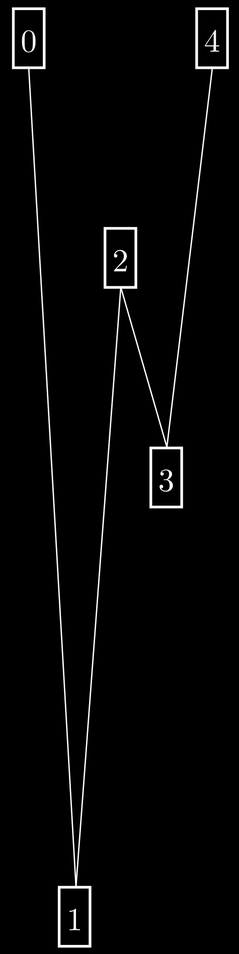
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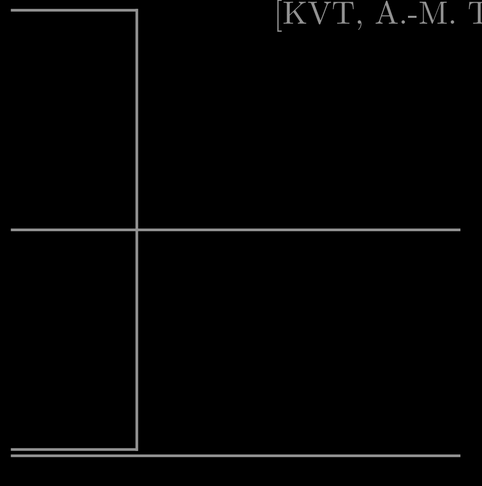
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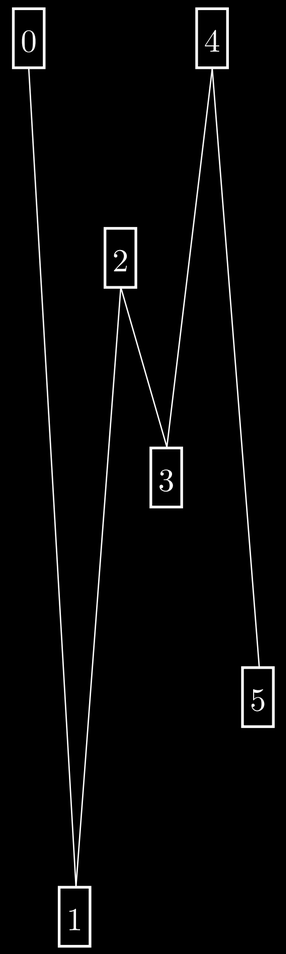
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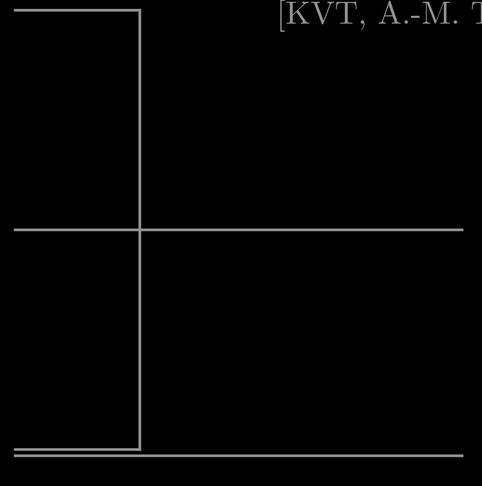
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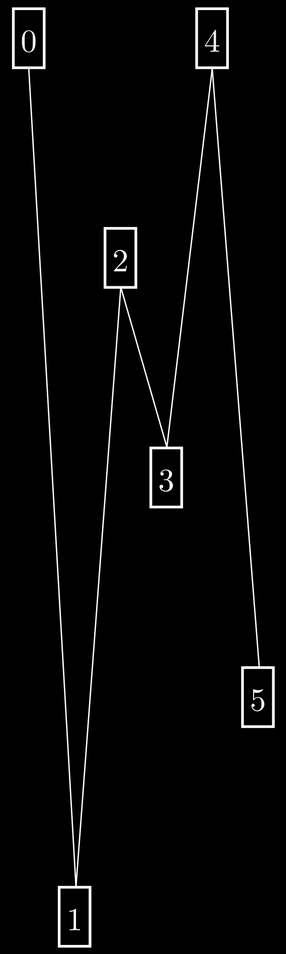
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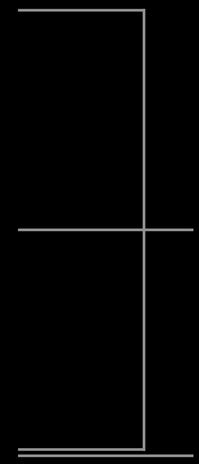
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   Small-scale structure as a probe of DM microphysics and primordial curvature

2. Signature

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   Acceleration and stochastic observables; instrumental, intrinsic, stellar backgrounds

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   Amplitude interferometry, *Gaia* DR3, *HST*, *JWST*

5. Future Data

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5. Future Data

   Intensity interferometry + EPIC

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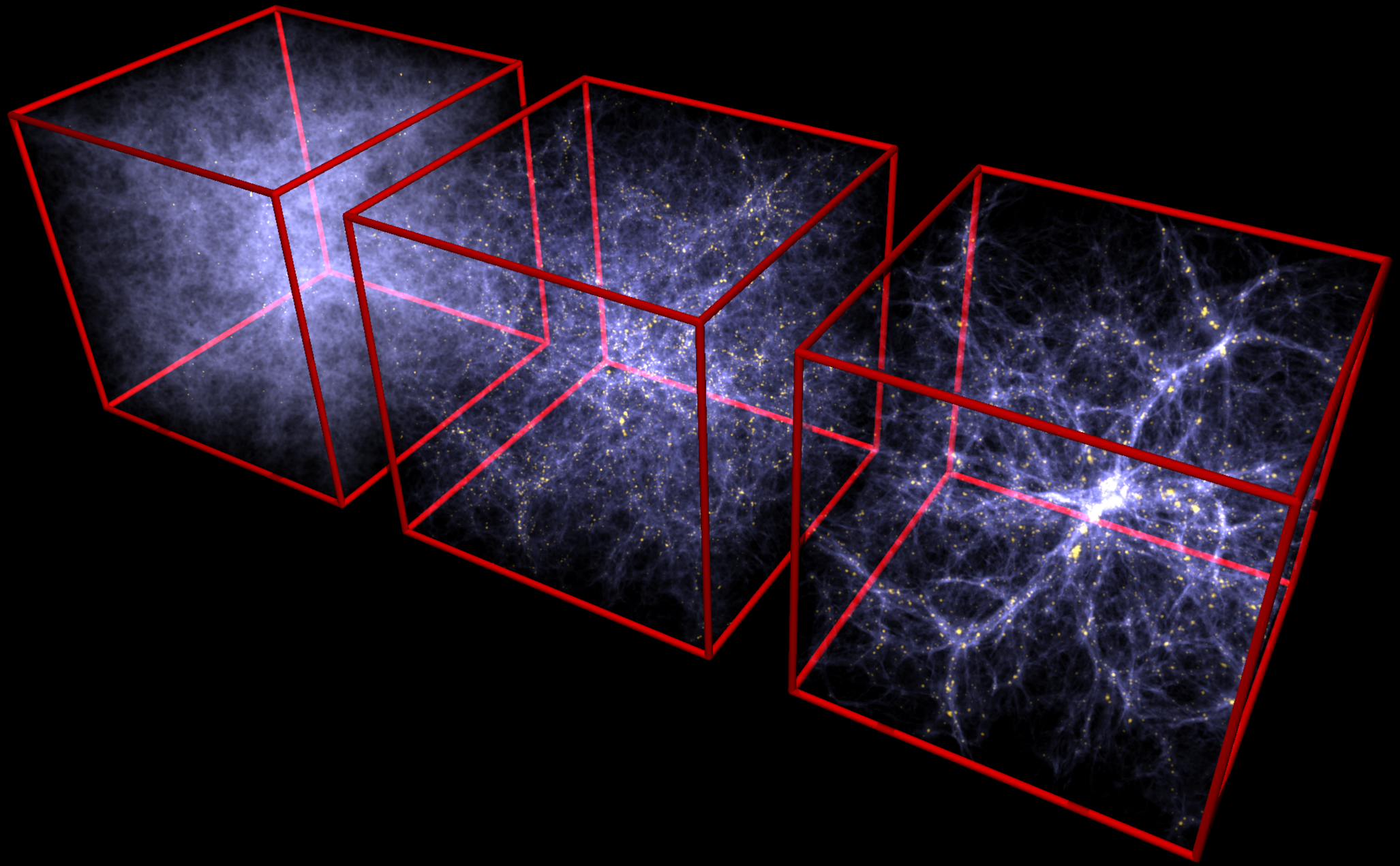
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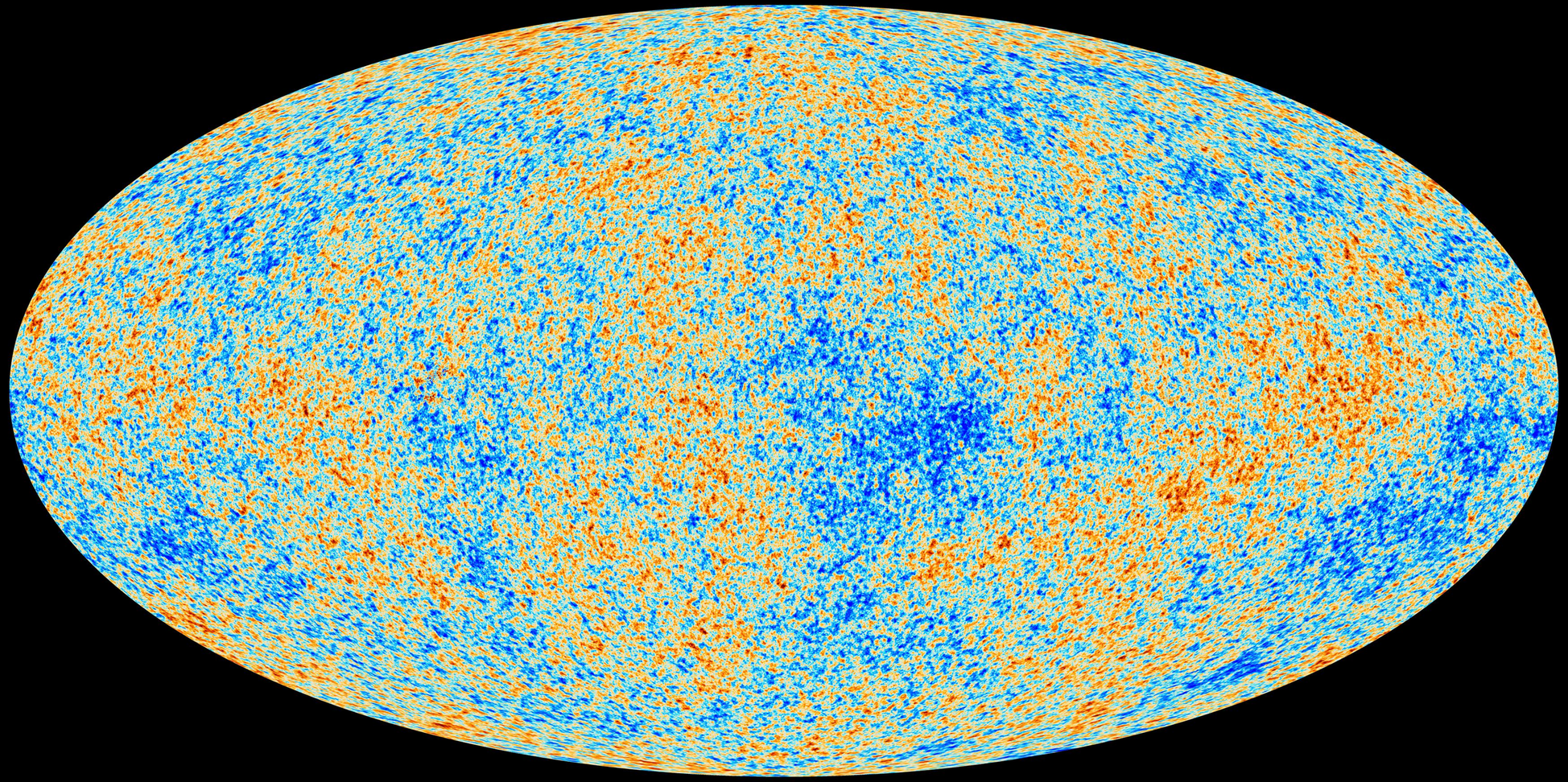
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Structure on Large Scales



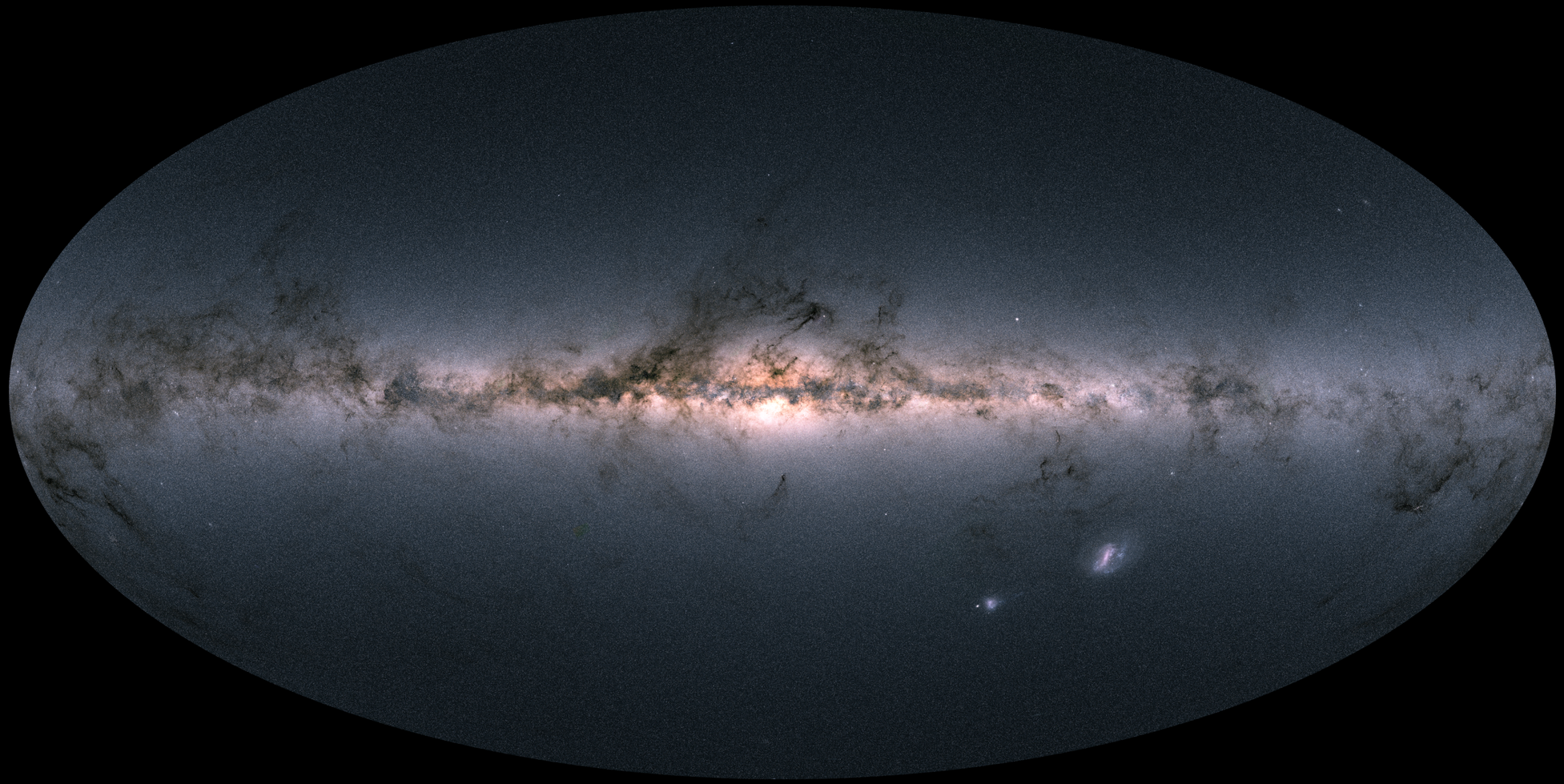
[MPA]

Structure on Super Large Scales



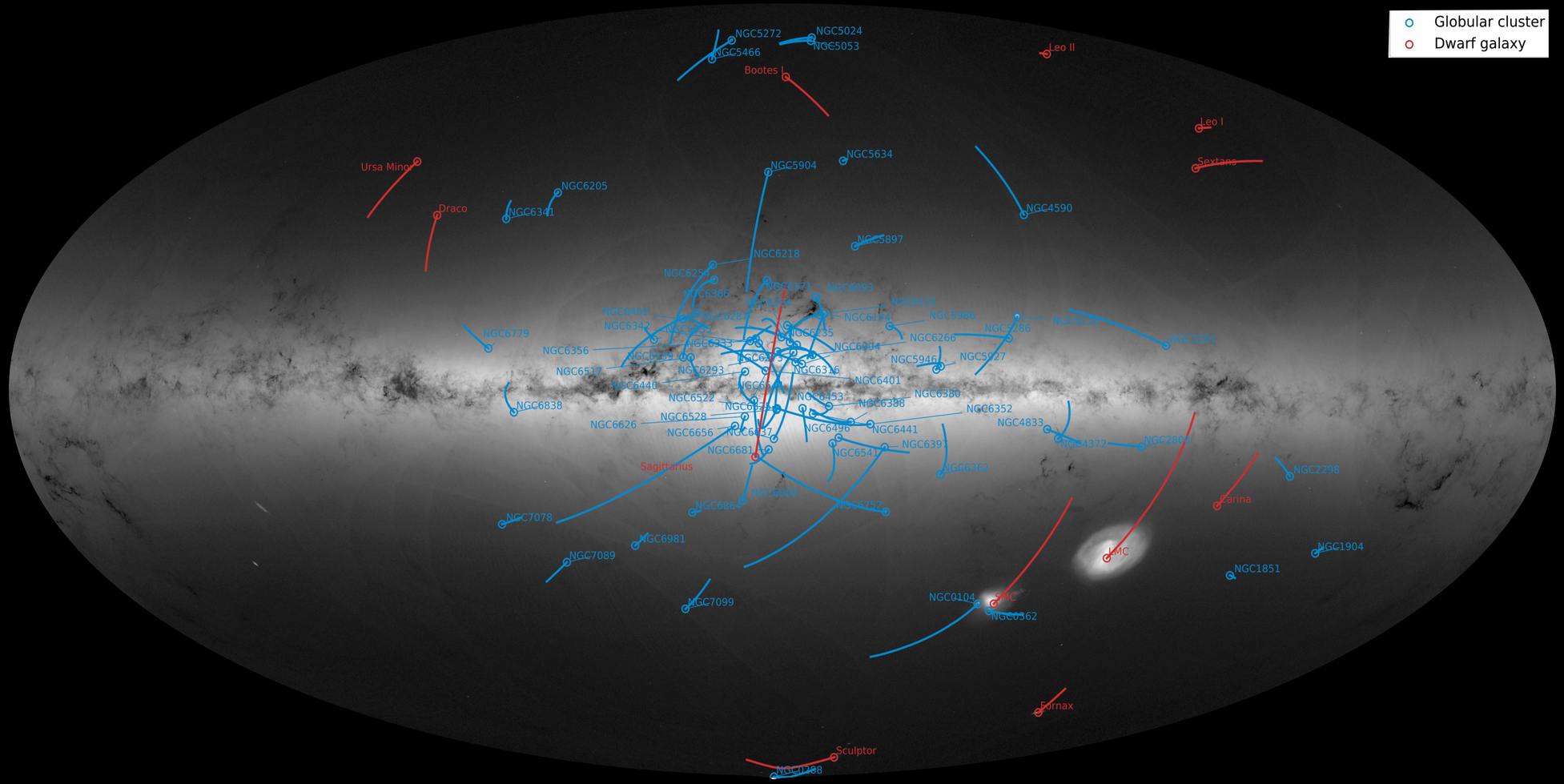
[*Planck*]

Structure on Medium Scales



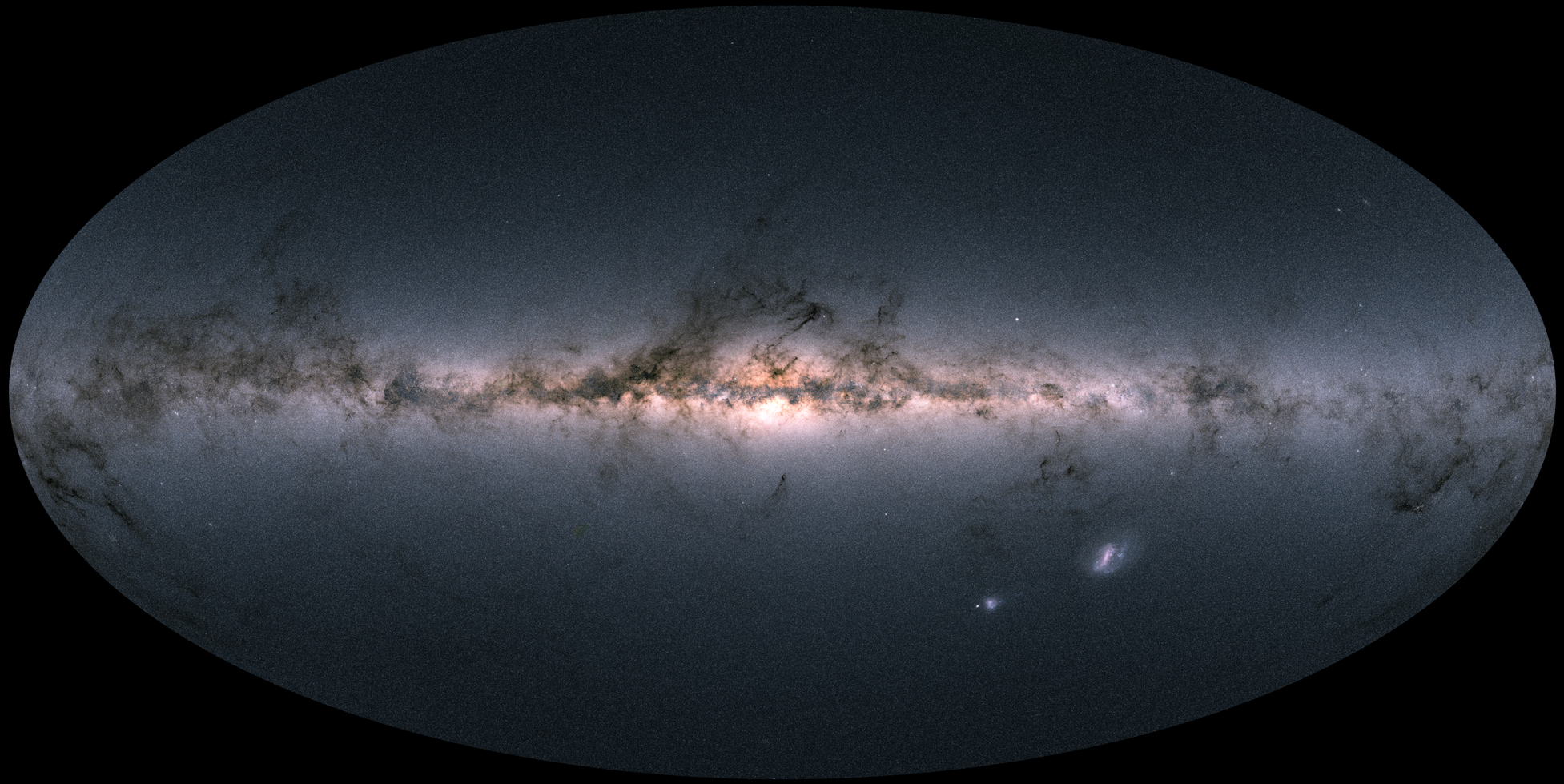
[*Gaia*]

Structure on Smallish Scales



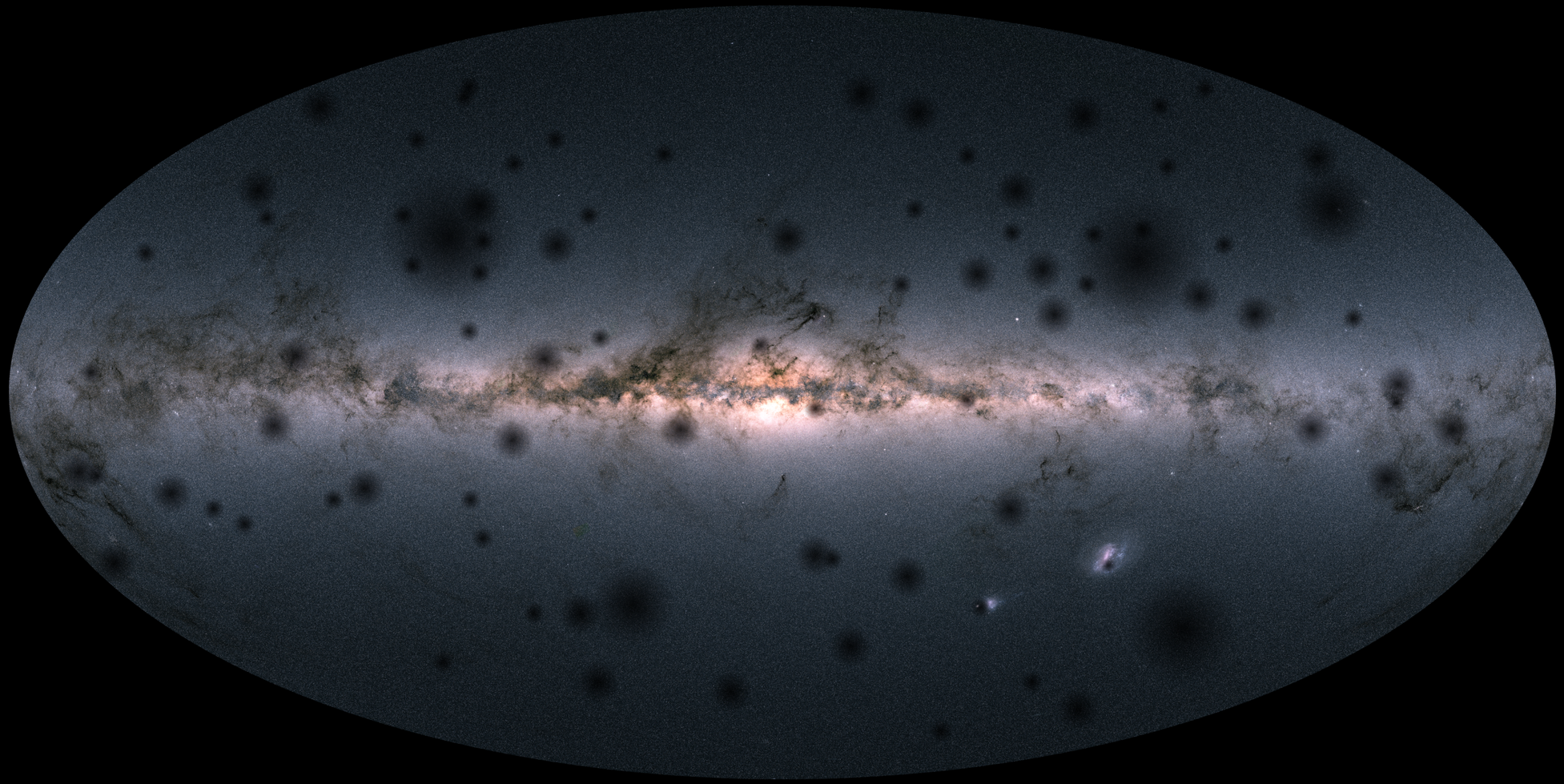
[Gaia]

Structure on Small Scales



[*Gaia*]

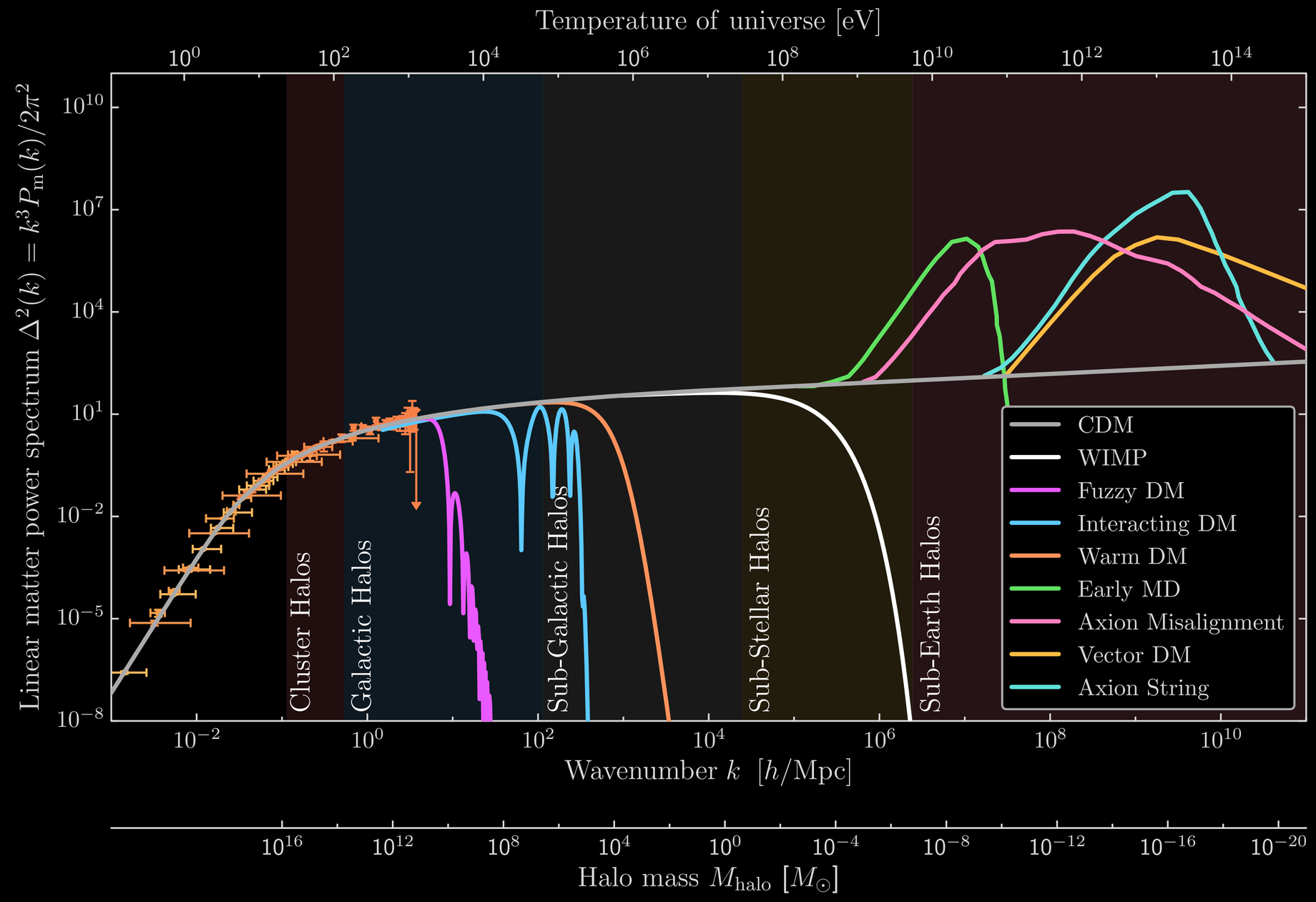
Structure on Small Scales



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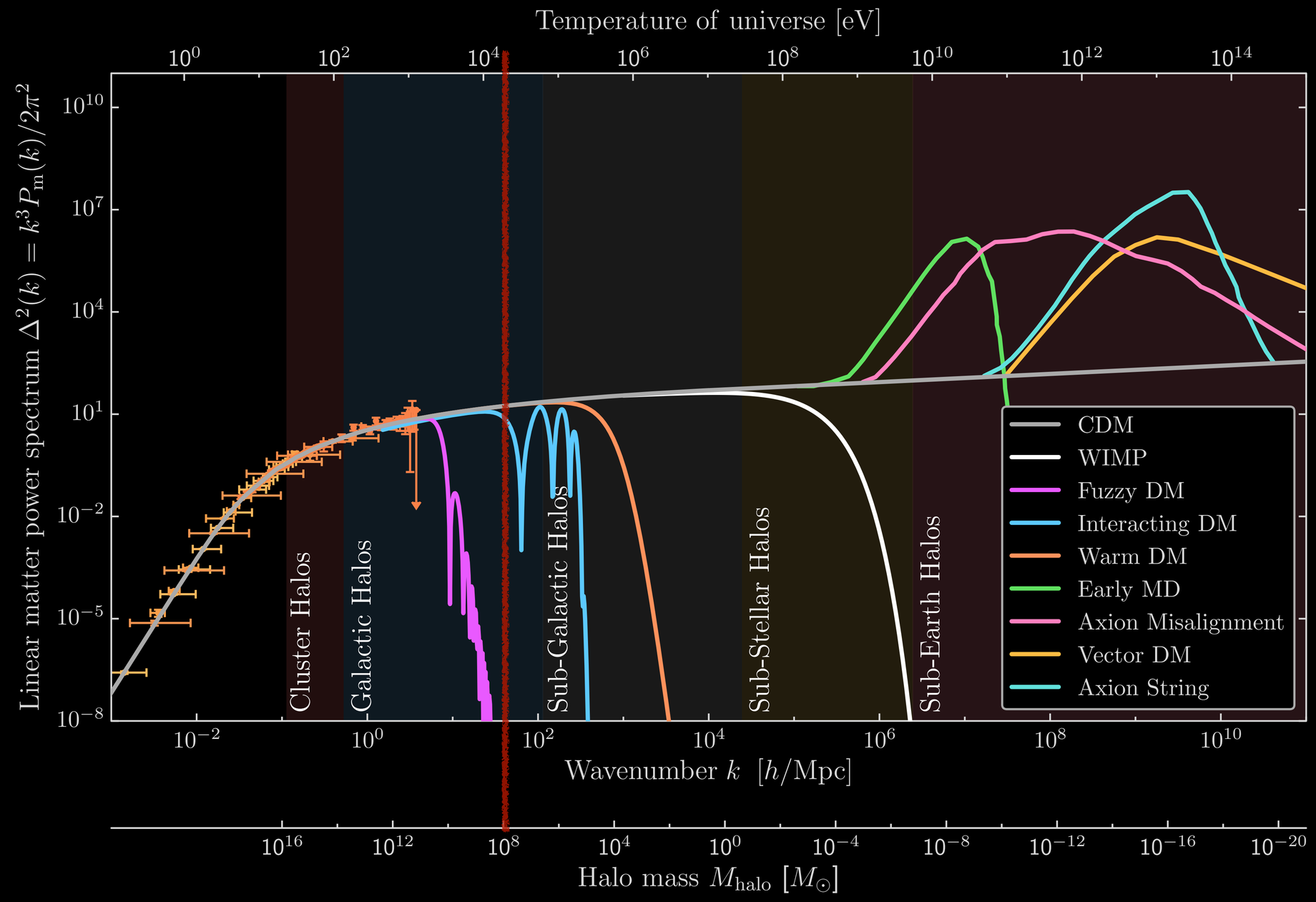
Structure on Super Small Scales

[arXiv:2203.07354]



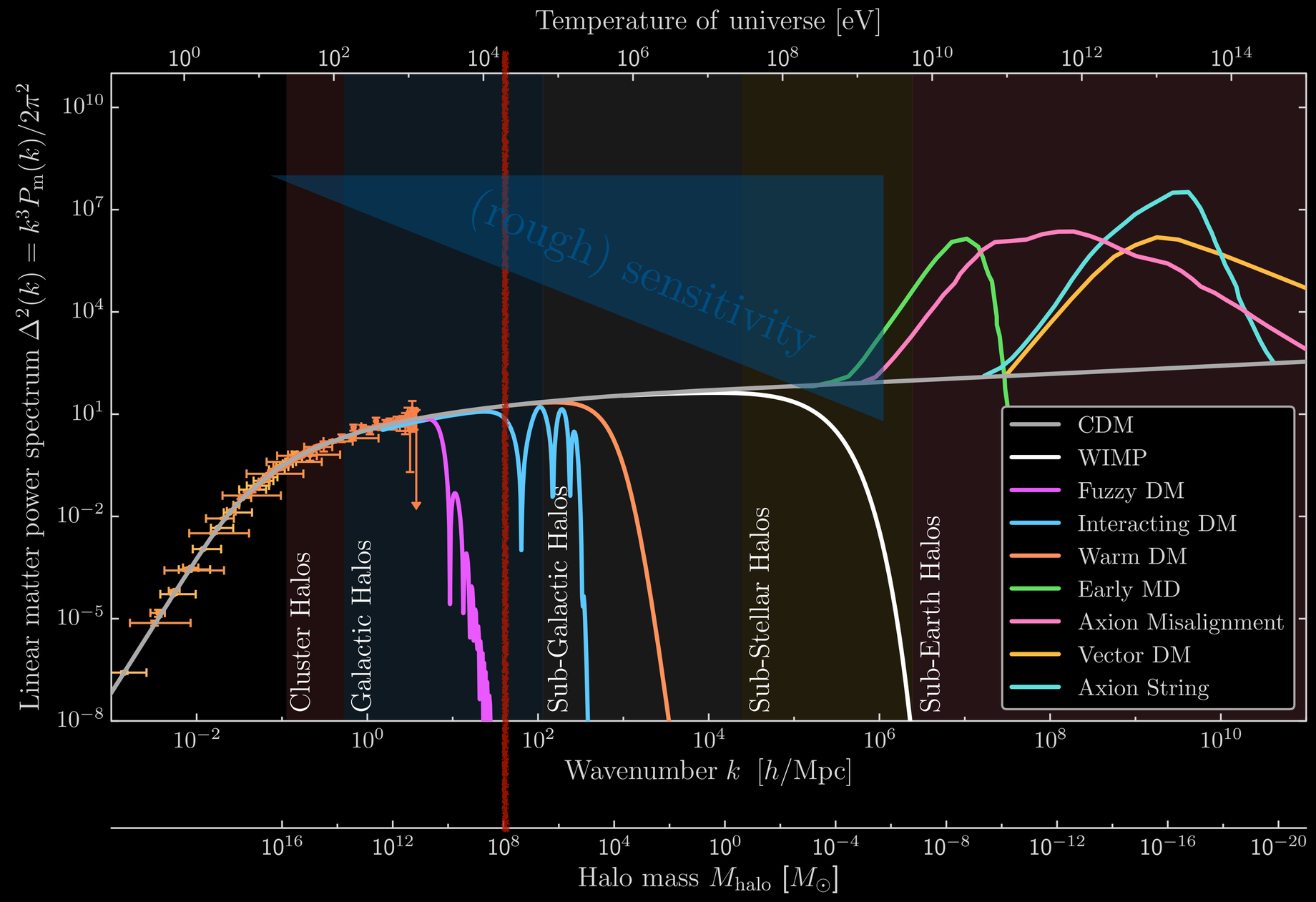
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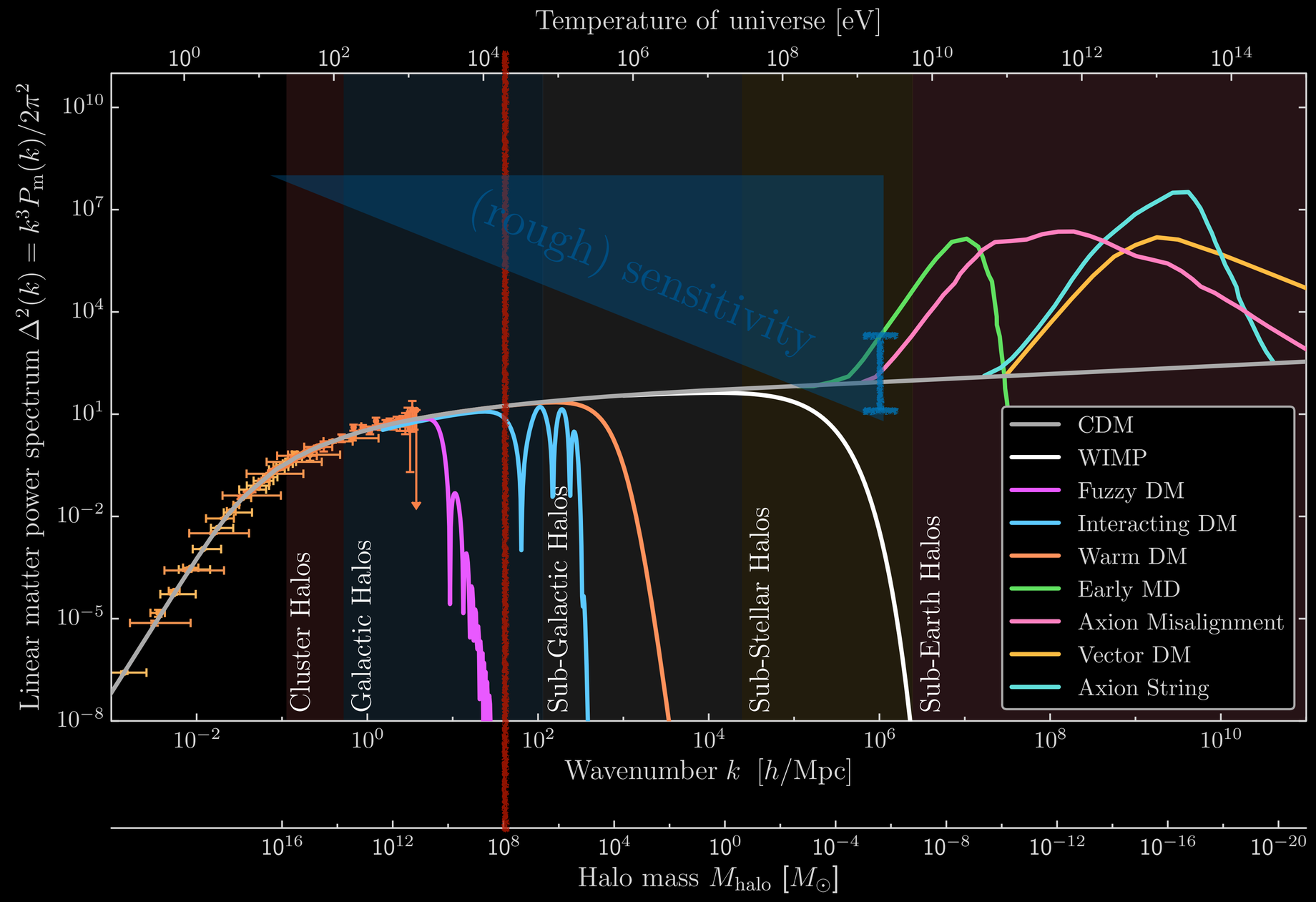
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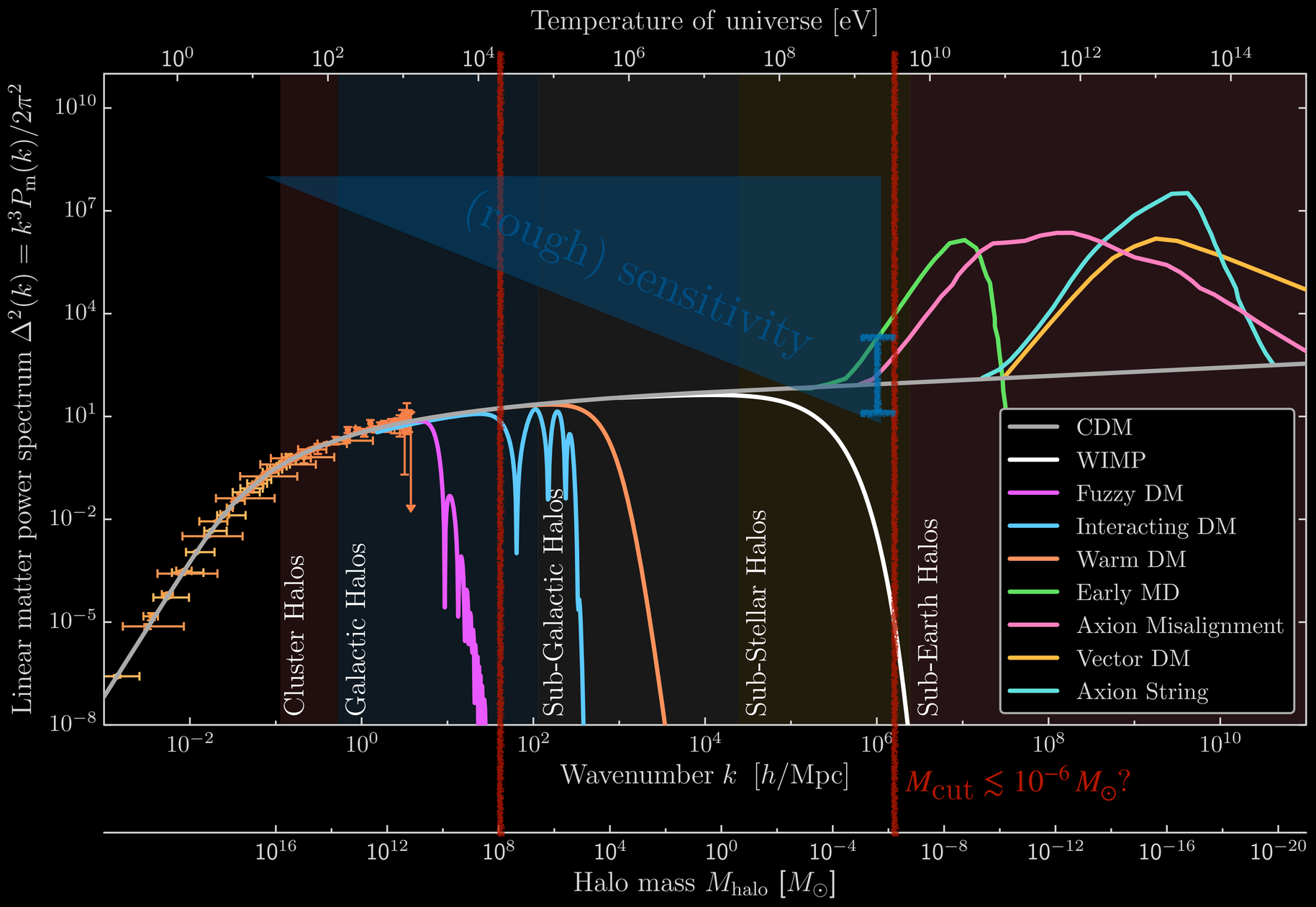
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Dark Matter Microphysics Implications

$$M_{\rm cut} \lesssim 10^{-6}\, M_\odot$$

Dark Matter Microphysics Implications

$$M_{\rm cut} \lesssim 10^{-6}\, M_\odot$$

$$\Downarrow$$

Universal lower limits on DM mass

$$m_{\rm fermion} \gtrsim \frac{\rho_s^{1/8} M_{\rm Pl}^{3/4}}{M_{\rm cut}^{1/4}} \gtrsim 400\,{\rm keV} \qquad \text{(degeneracy pressure)}$$

Dark Matter Microphysics Implications

$$M_{\rm cut} \lesssim 10^{-6}\, M_\odot$$

$$\Downarrow$$

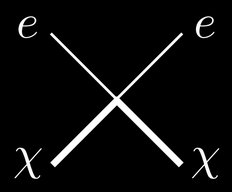
Universal lower limits on DM mass

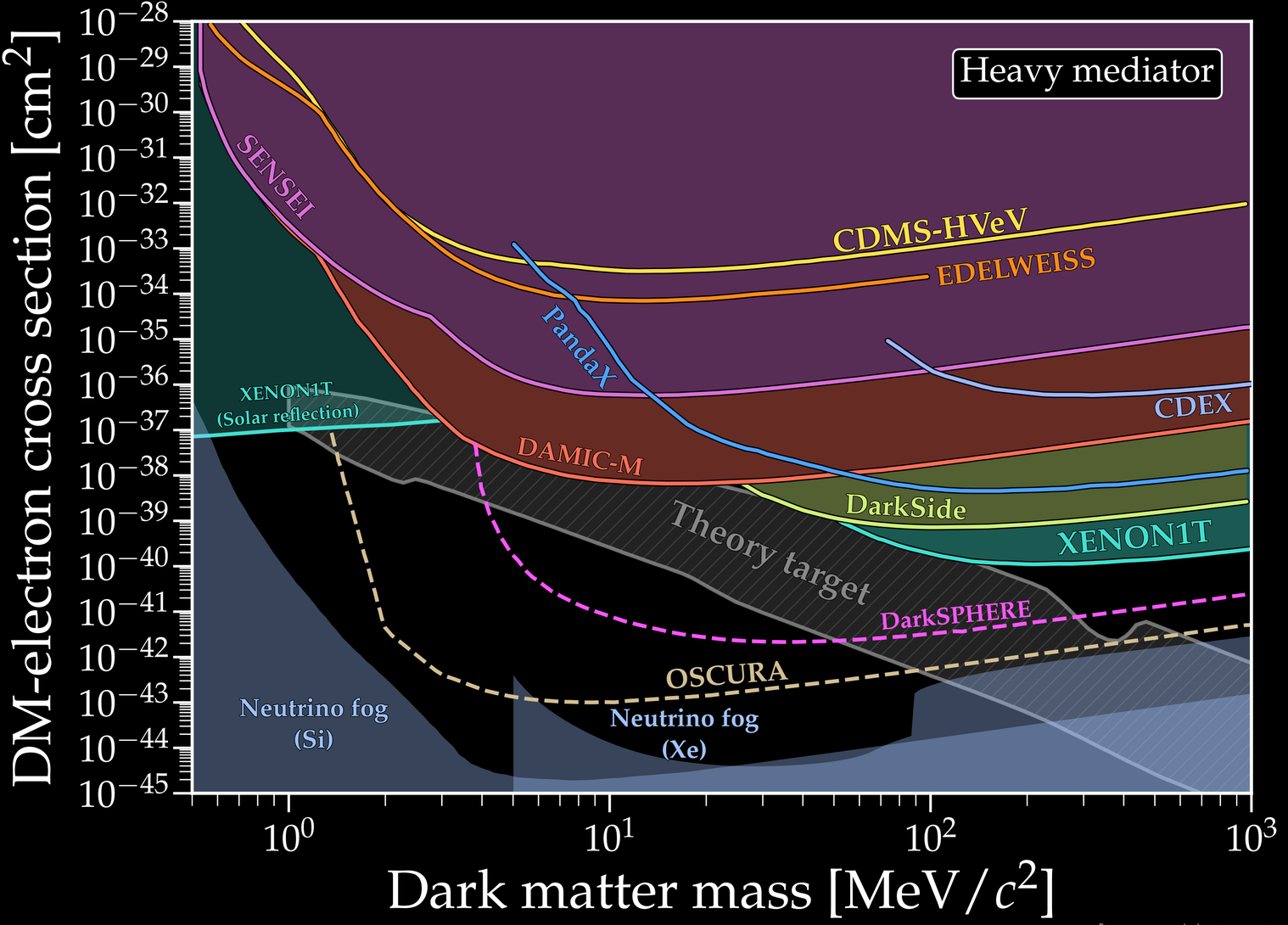
$$m_{\rm fermion} \gtrsim \frac{\rho_s^{1/8} M_{\rm Pl}^{3/4}}{M_{\rm cut}^{1/4}} \gtrsim 400\,{\rm keV} \qquad \text{(degeneracy pressure)}$$

$$m_{\rm boson} \gtrsim \frac{H_{\rm eq}^{1/3} M_{\rm Pl}^{4/3}}{M_{\rm cut}^{2/3}} \gtrsim 10^{-11}\,{\rm eV} \qquad \text{(gradient pressure)}$$

Dark Matter Microphysics Implications

Kinetic Decoupling

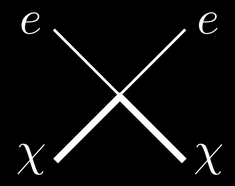


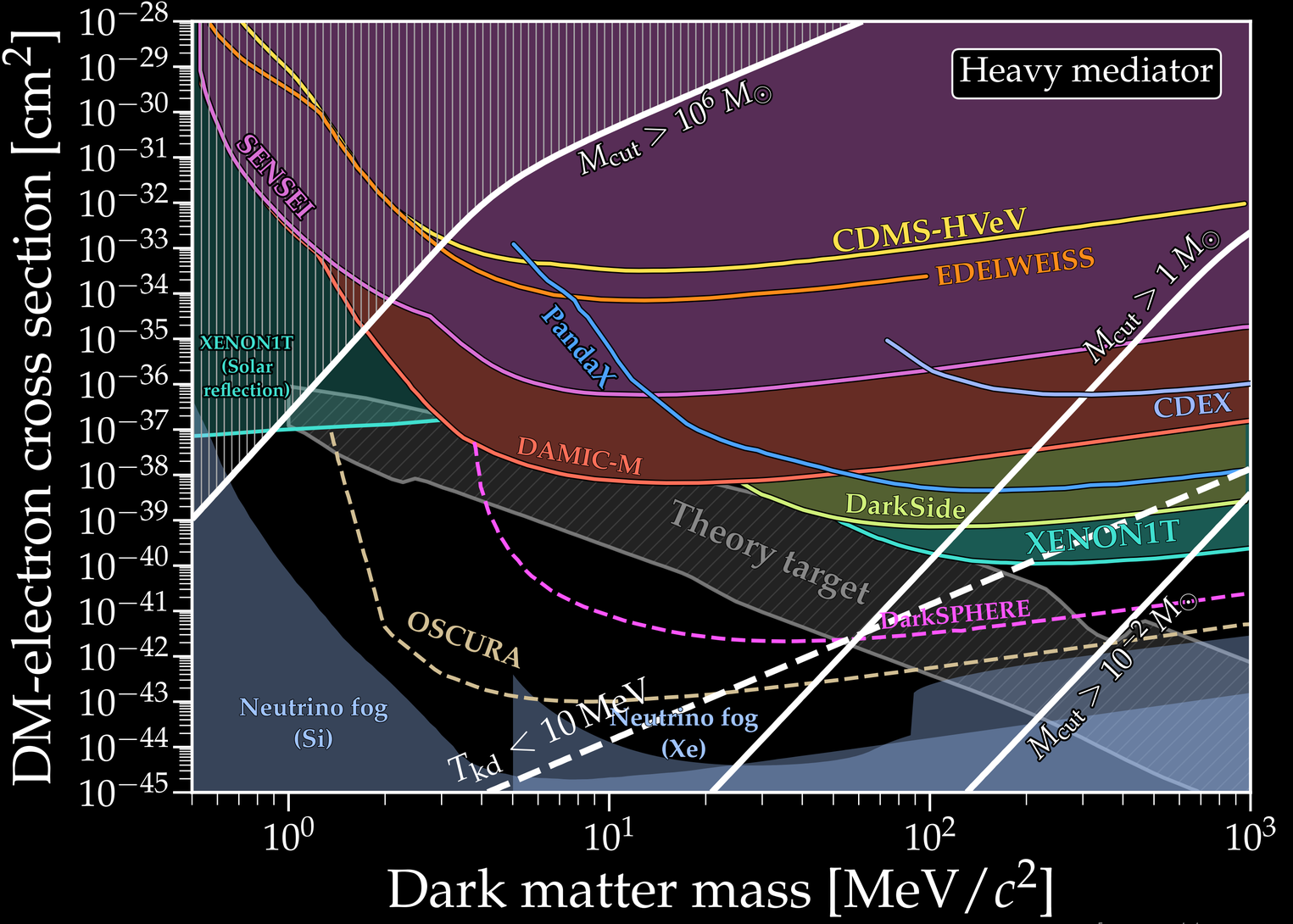


[https://github.com/cajohare/DirectDetectionPlots/]

Dark Matter Microphysics Implications

Kinetic Decoupling





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[KVT, D.E. Kaplan; 2608.27557]

[A. Moran, KVT; 2608.27577]

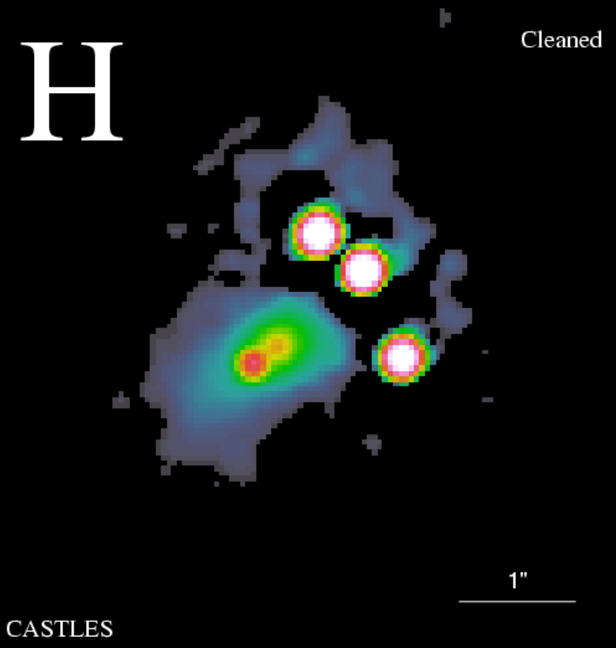
[KVT, M. Baryakhtar, M. Galanis, N. Weiner; arXiv:2307.03221]

[M. Galanis, KVT, M. Baryakhtar, N. Weiner; arXiv:2307.06989]

Macrolensing

Macrolensing

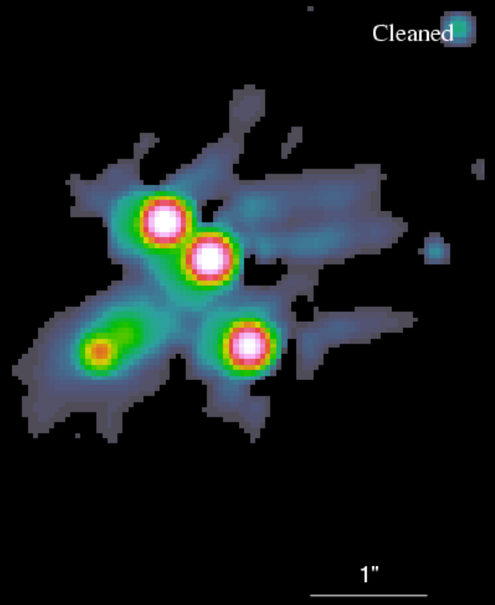
B1422+231



Macrolensing

B1422+231

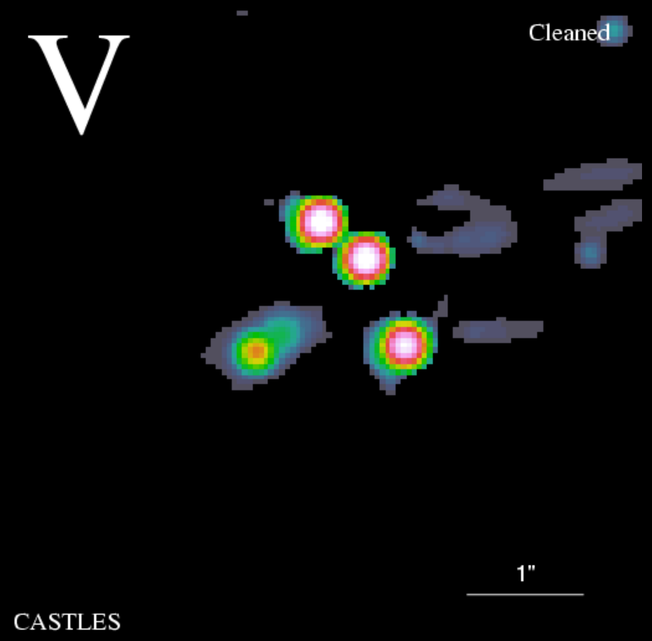
I



CASTLES

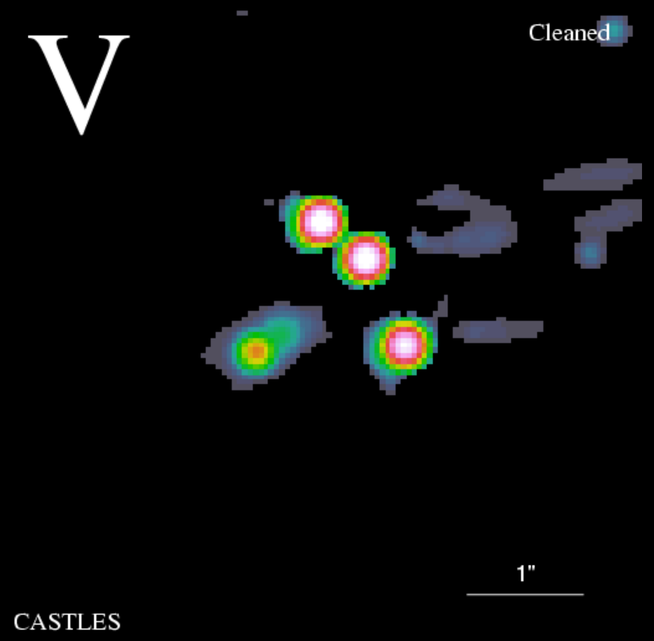
Macrolensing

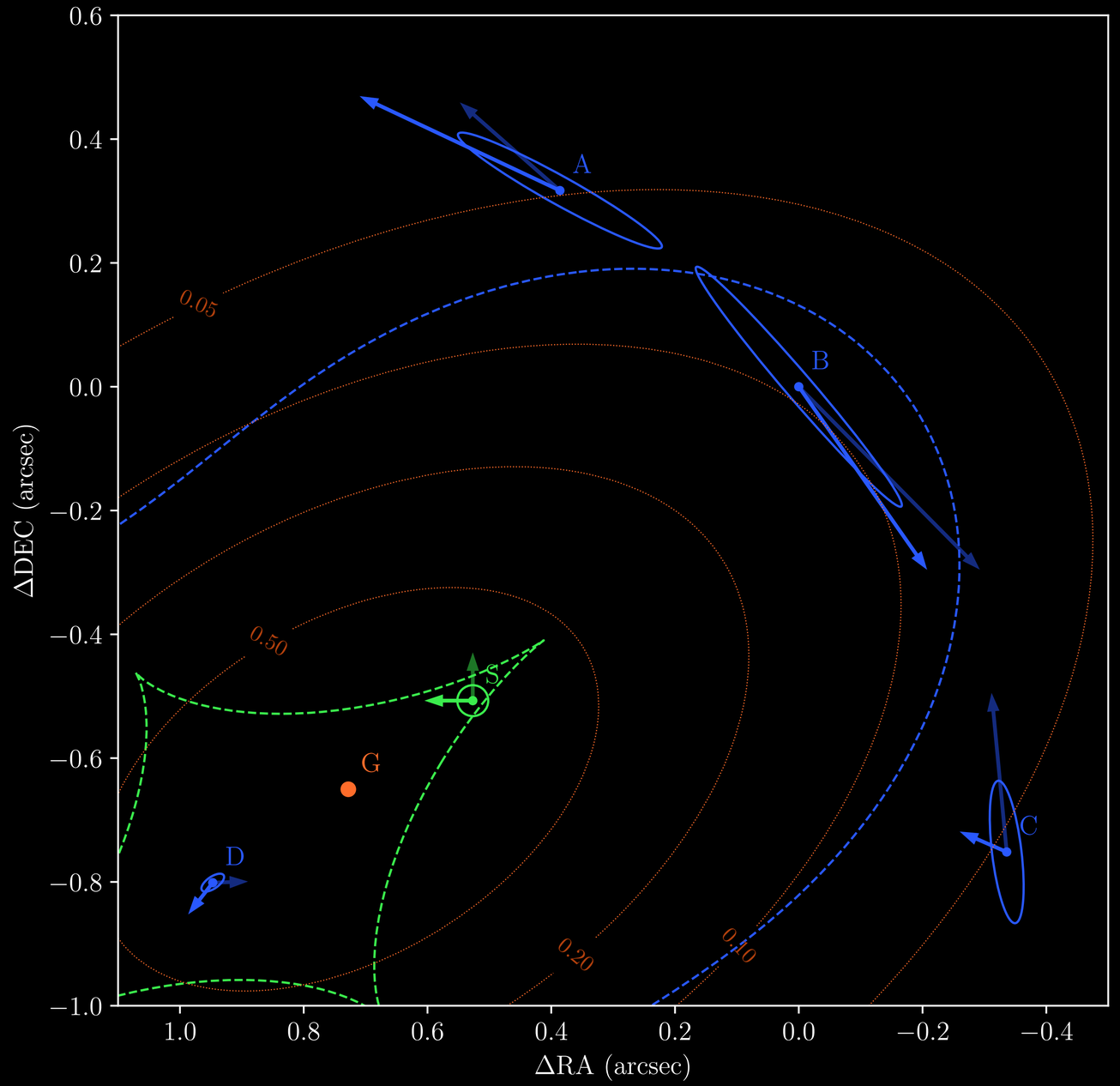
B1422+231



Macrolensing

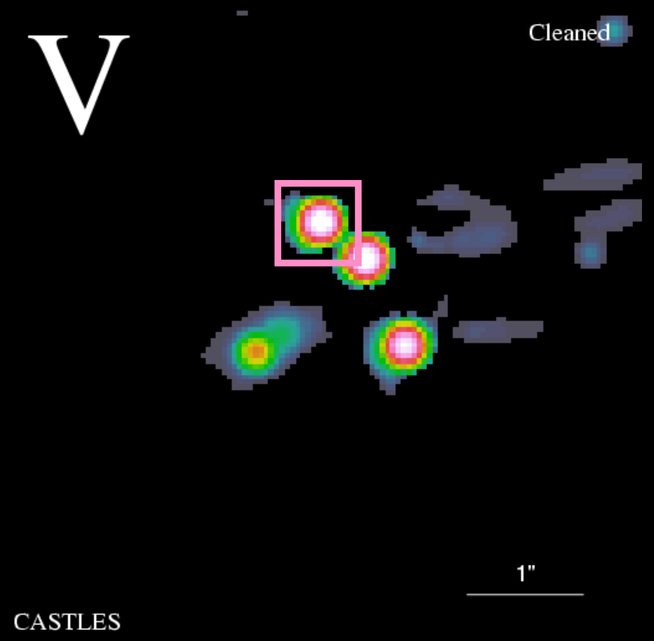
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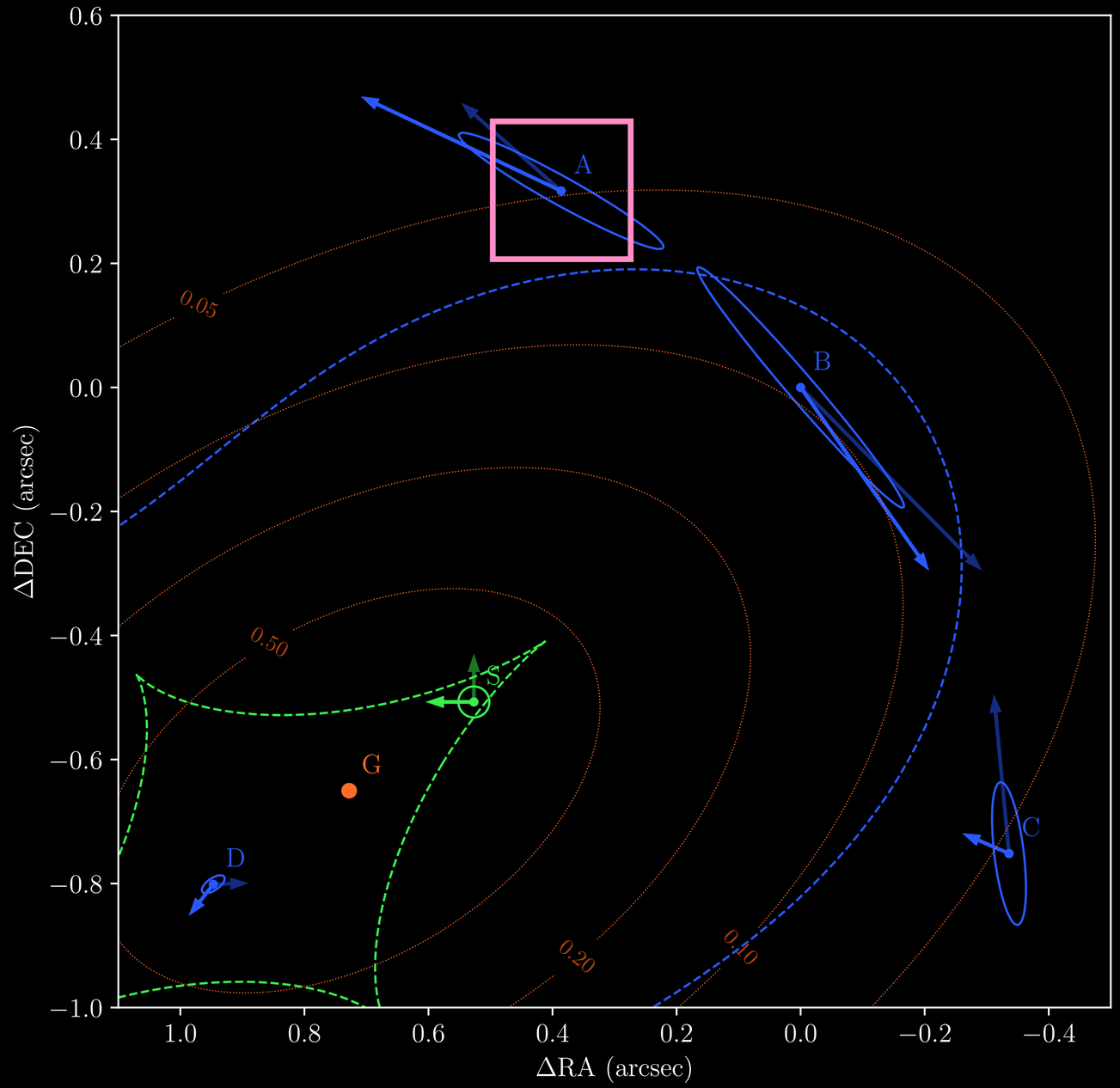




Macrolensing

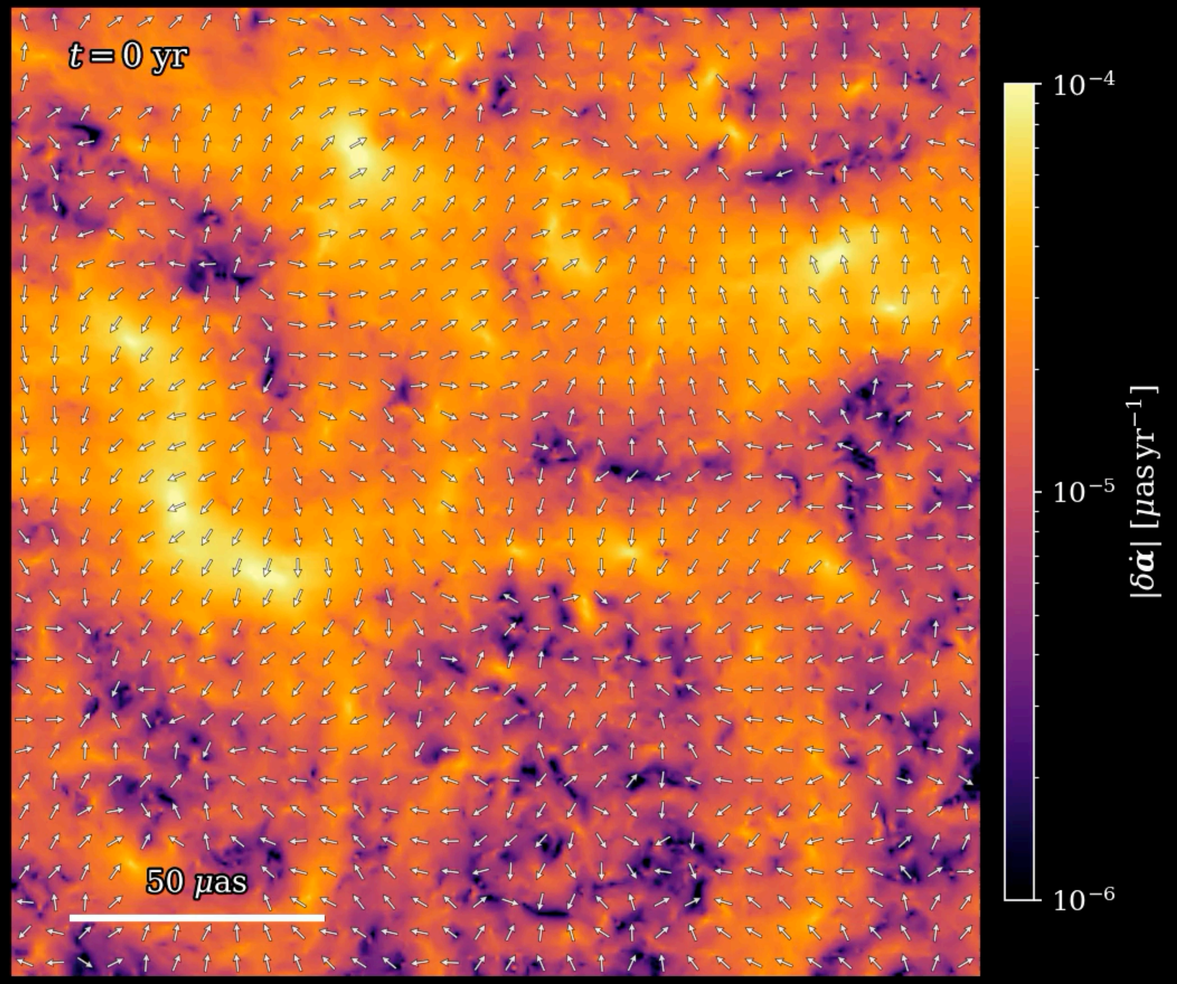
B1422+231



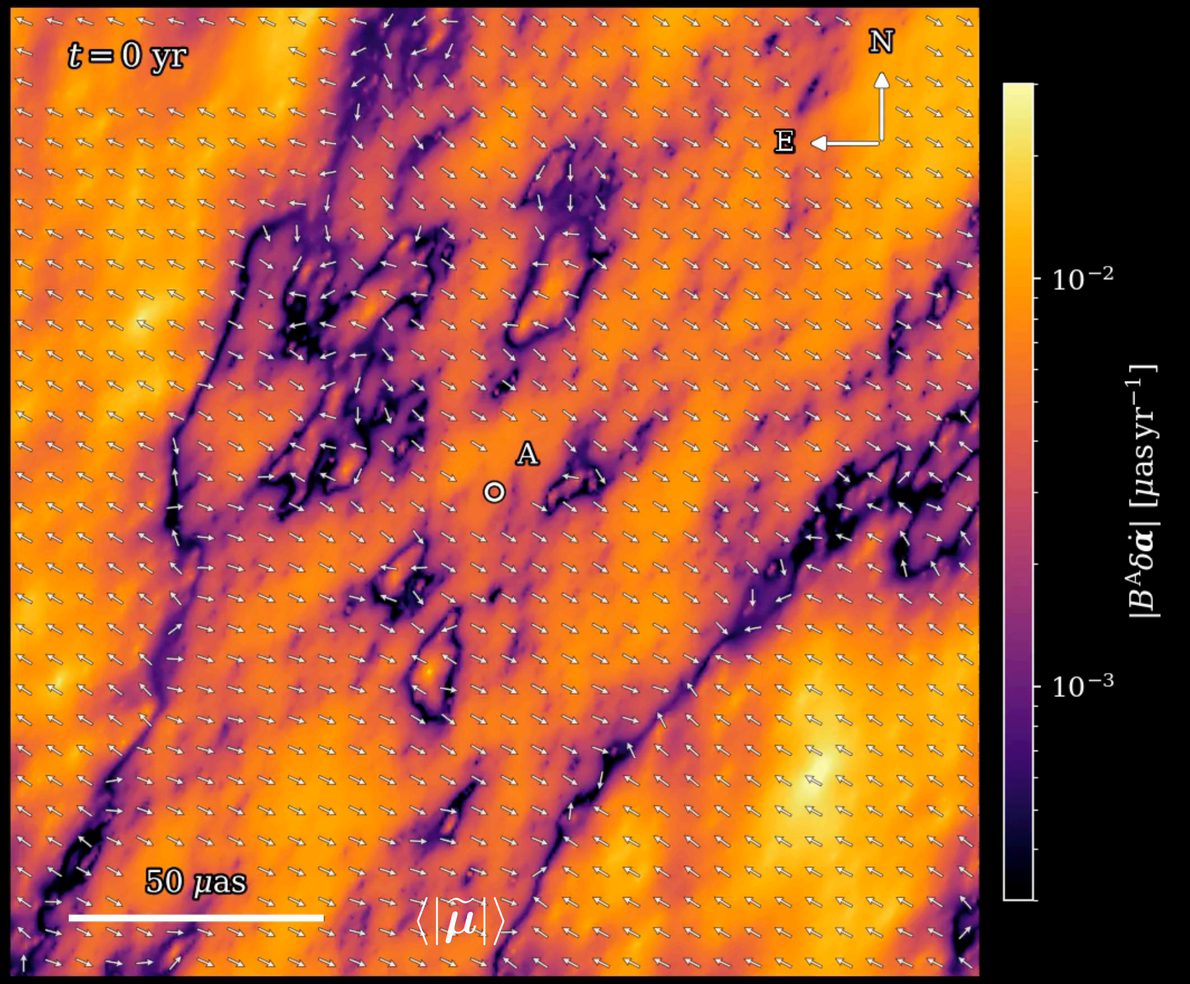


Magnified Stochastic Lensing Noise

Generic line of sight



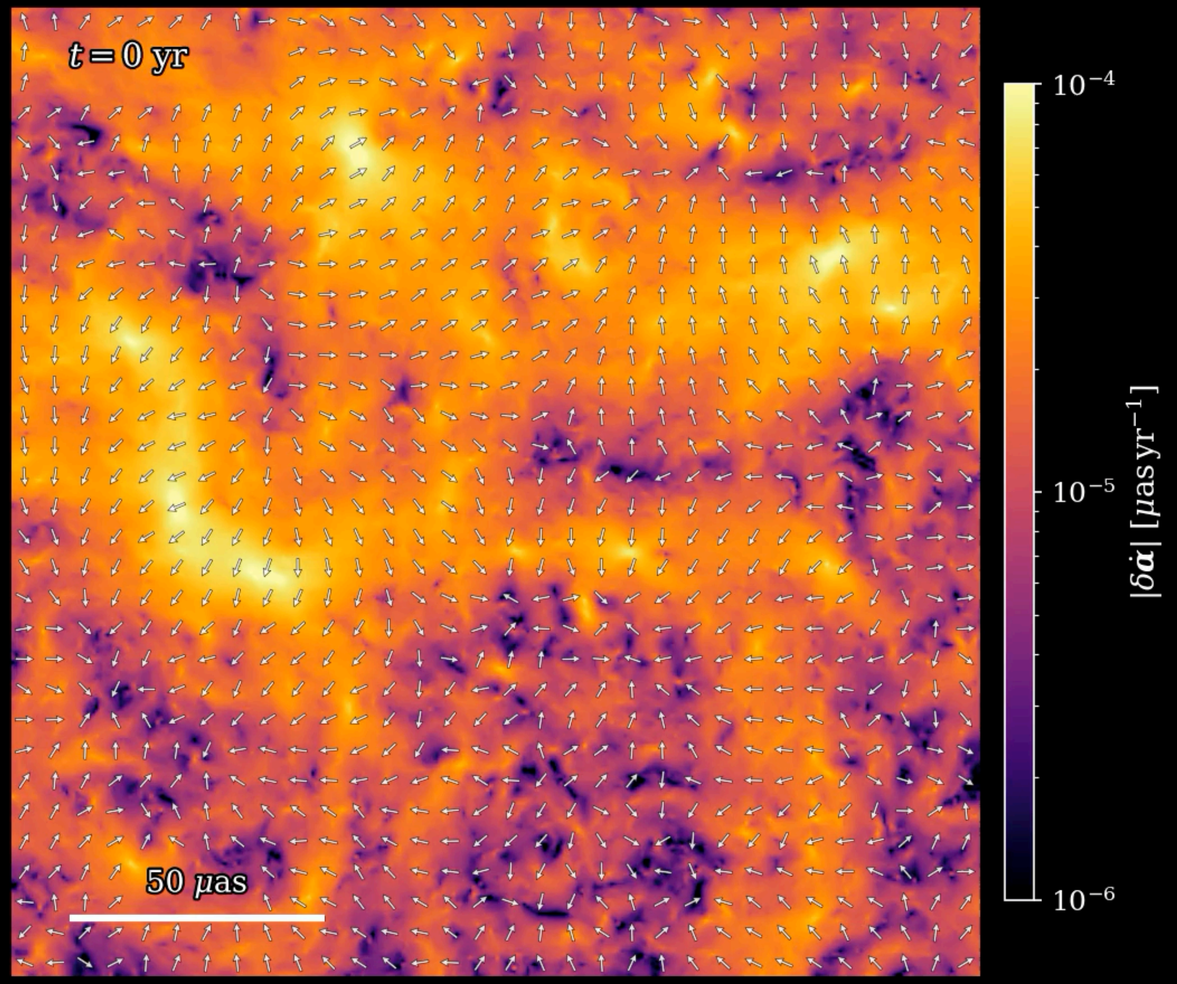
B1422+231 subhalos; image A fixed



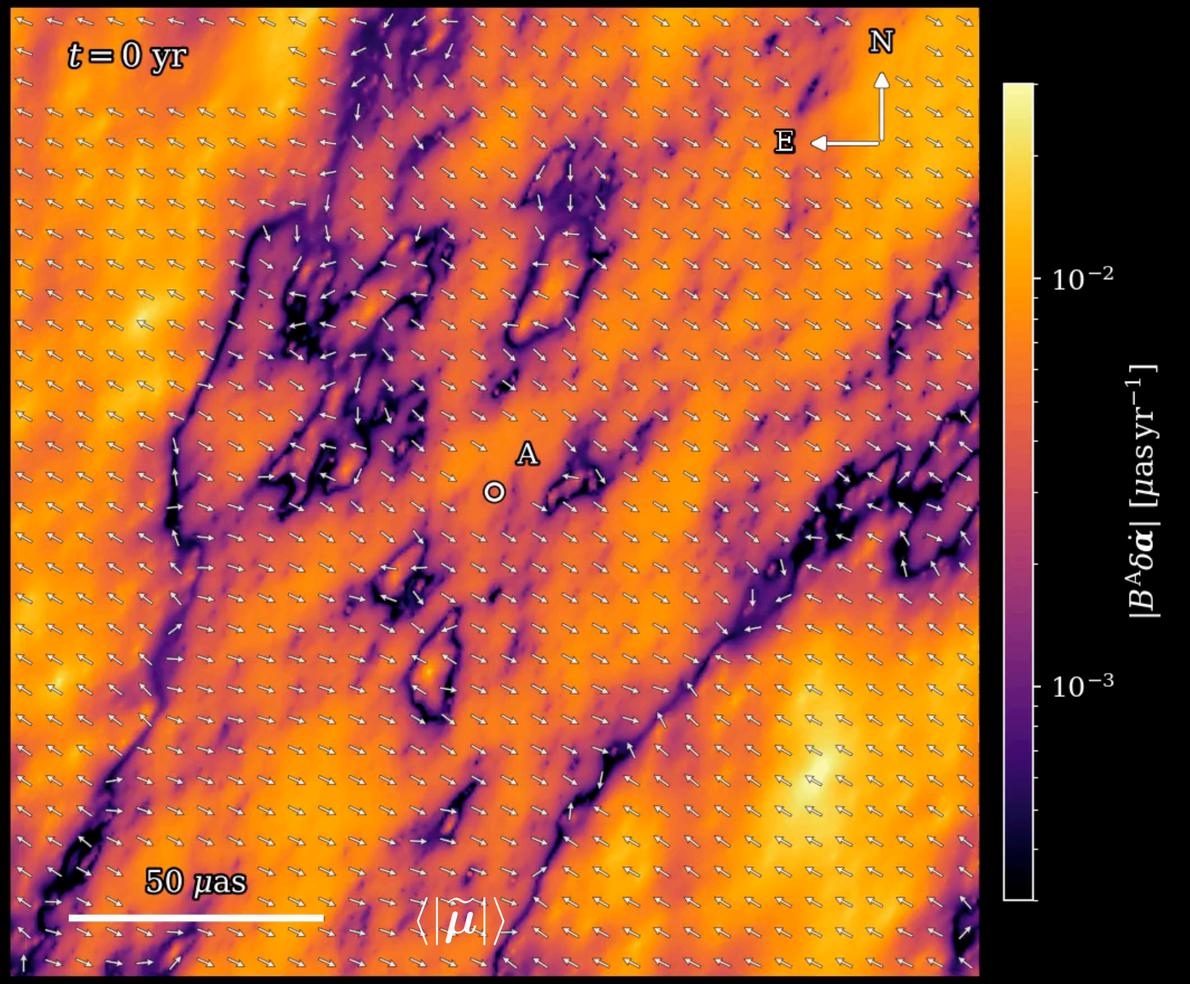
$\langle|\widetilde{\boldsymbol{\mu}}|\rangle \sim 1\,\mu\mathrm{as\,yr}^{-1}$

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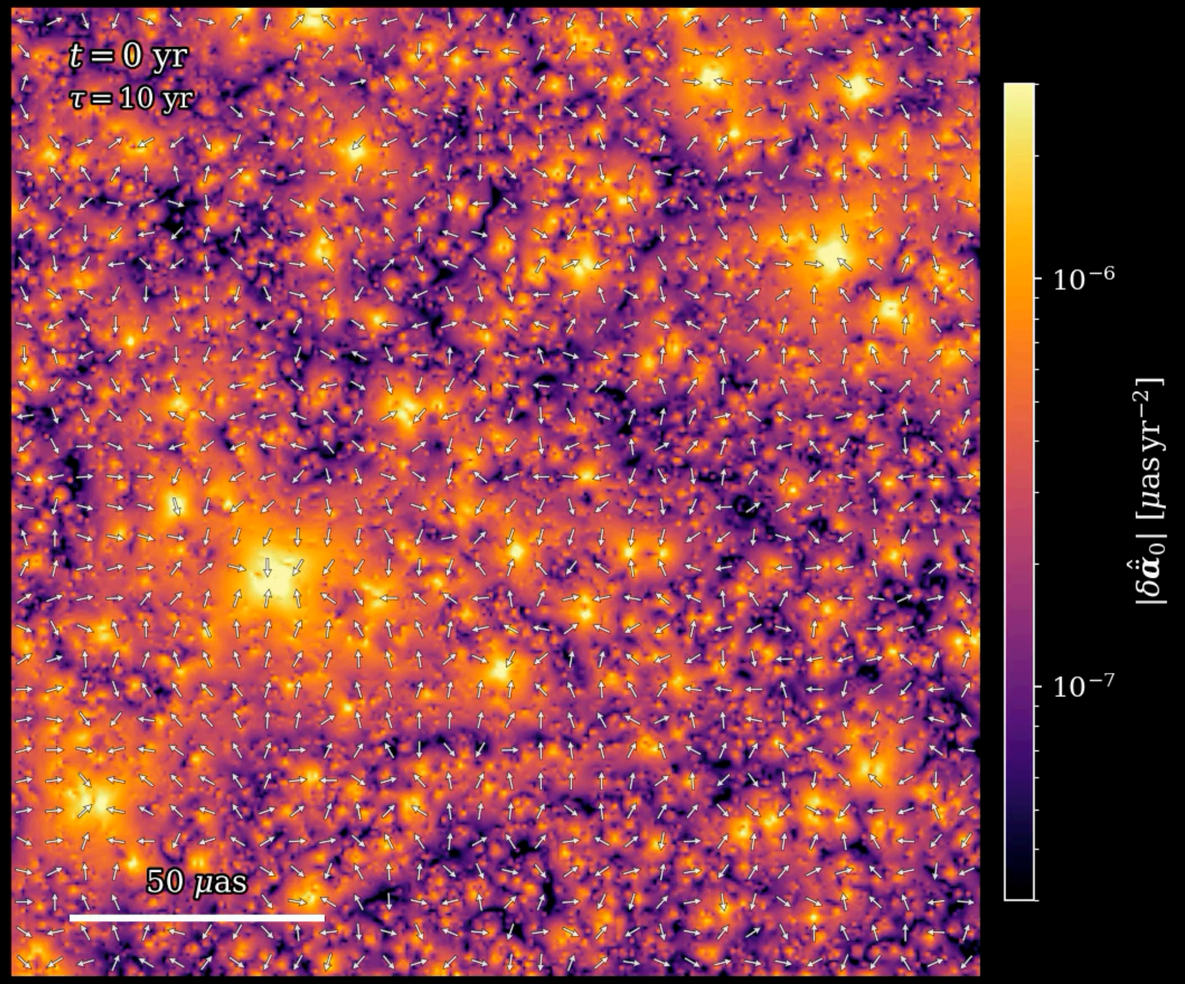
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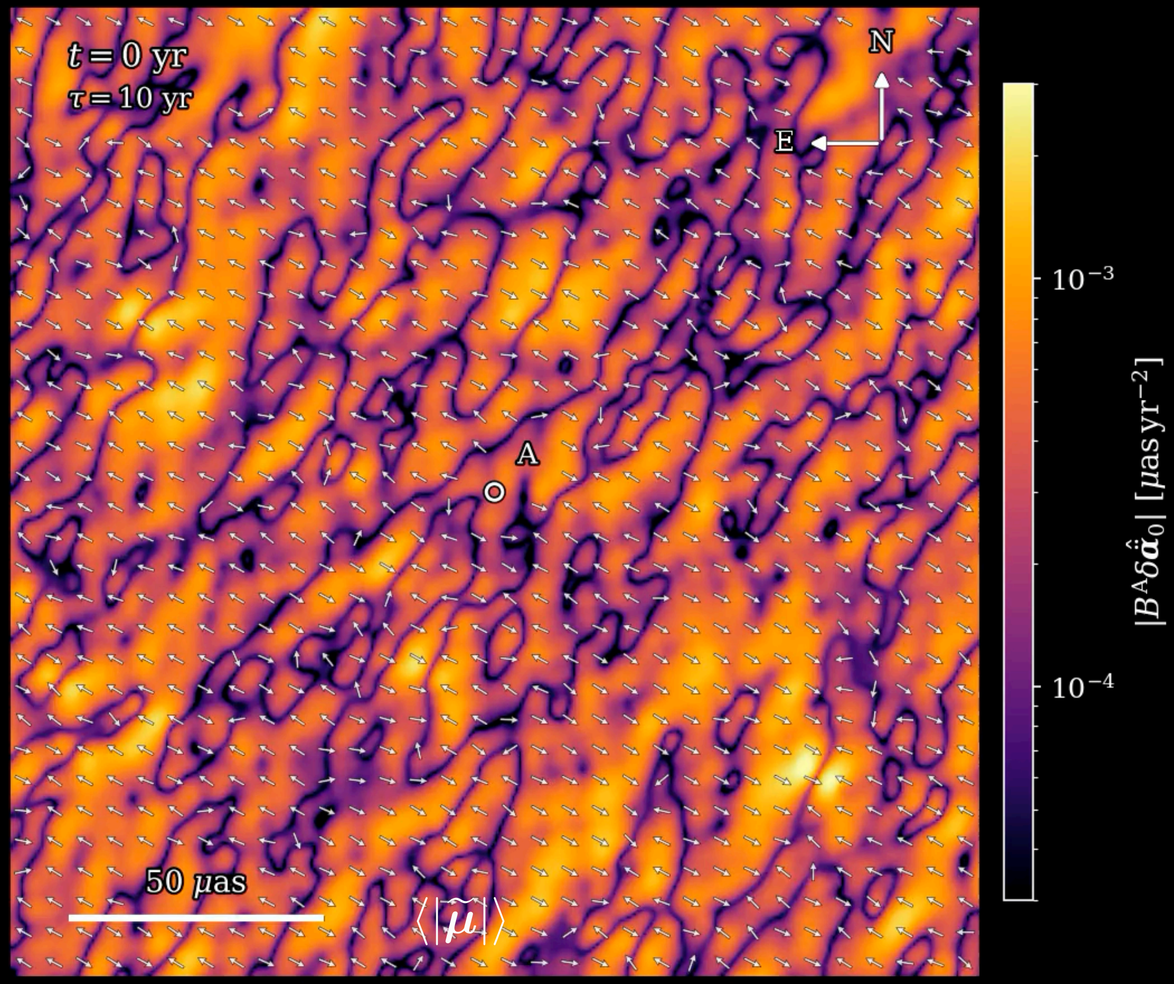
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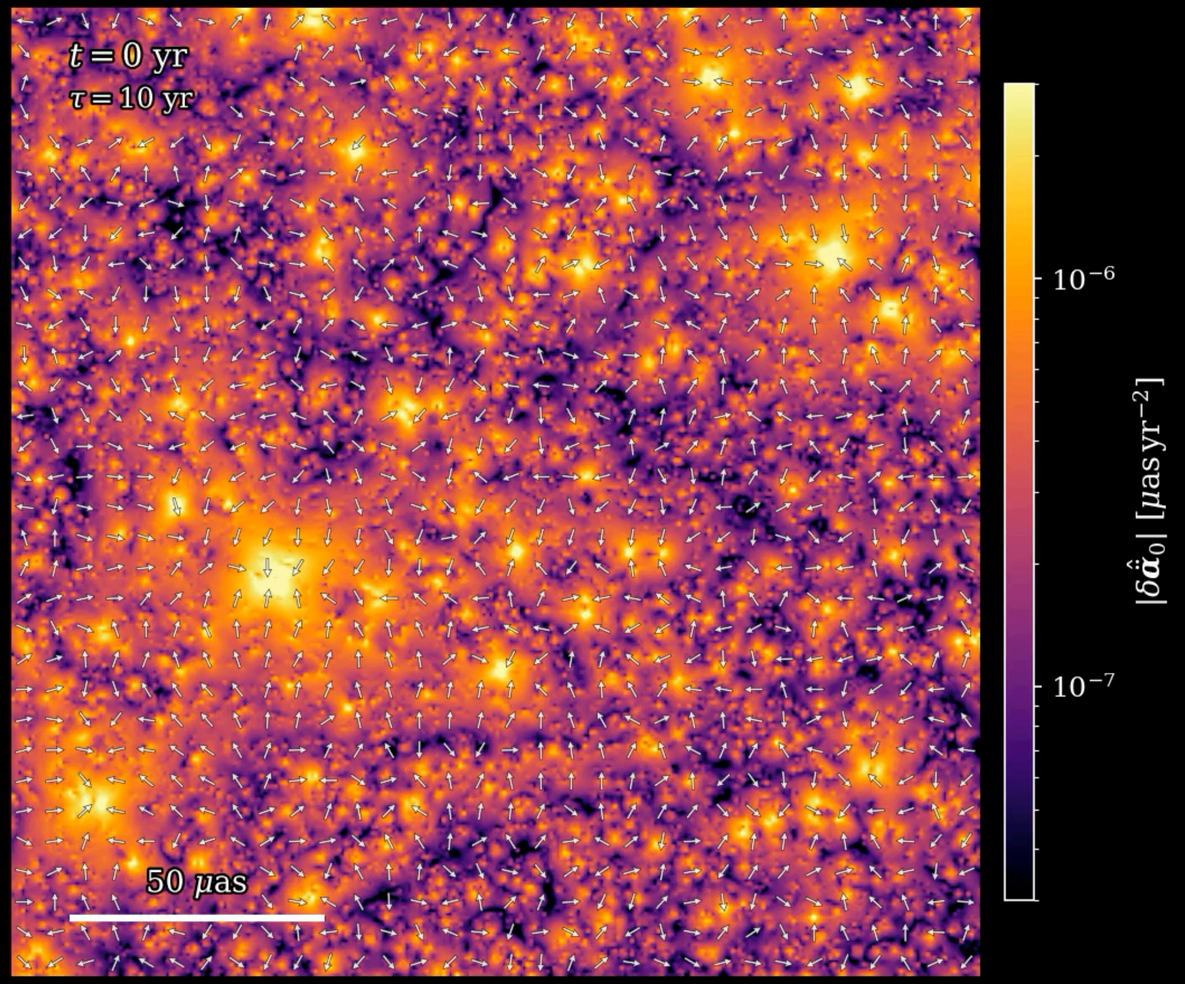
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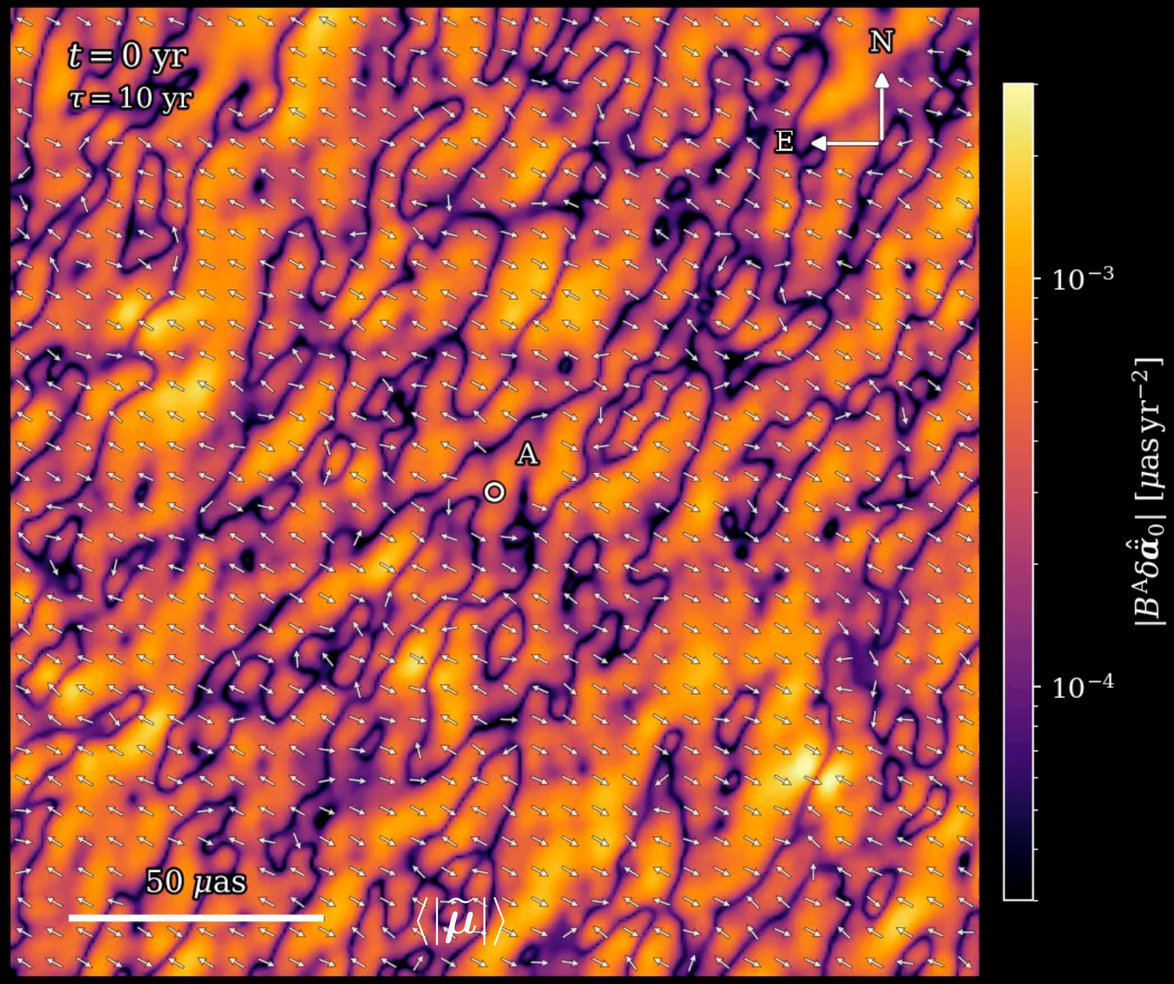
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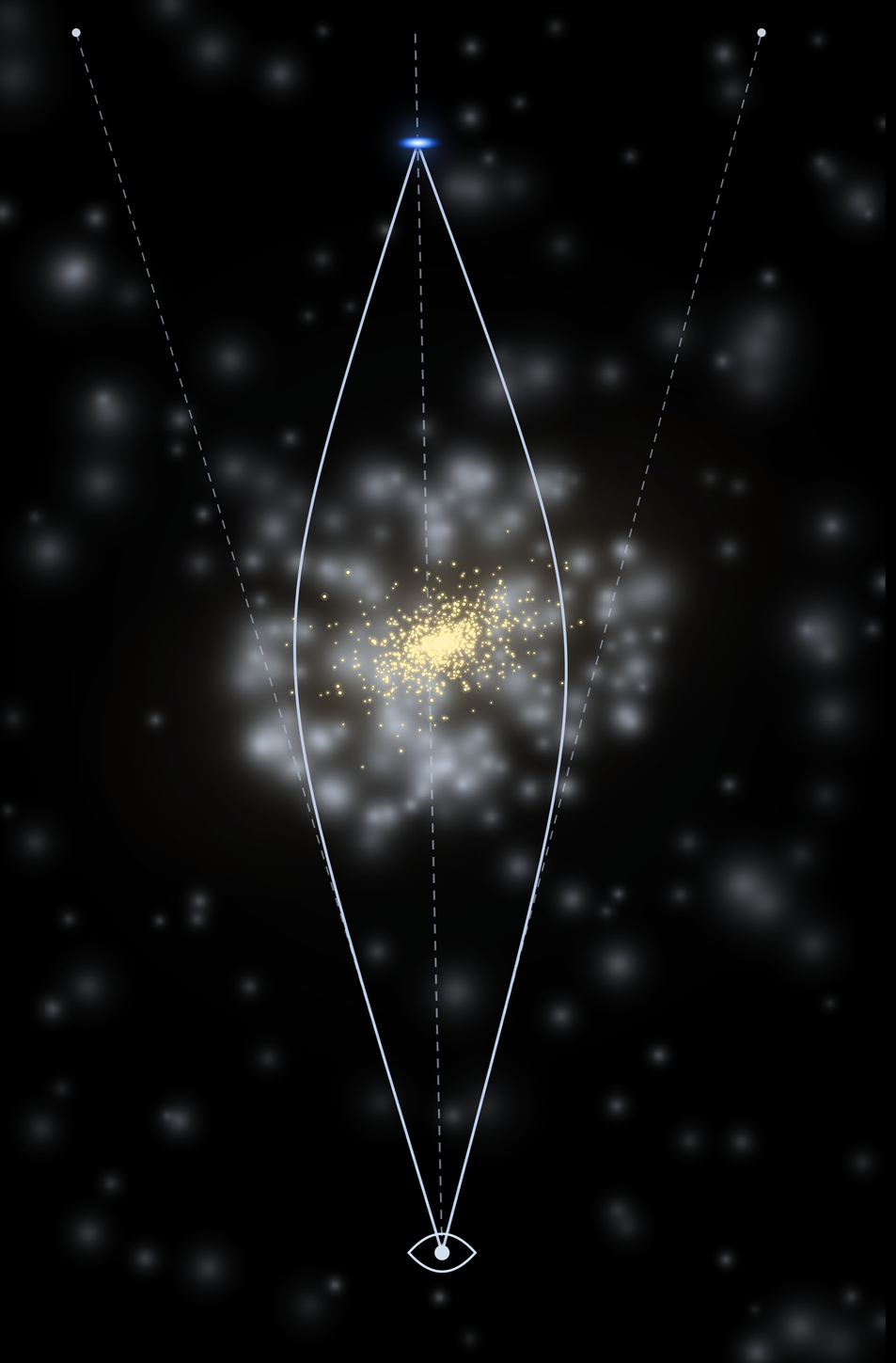
Generic line of sight



B1422+231 subhalos; image A fixed



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Quasar Lensing

Lens equation:

$$\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\alpha}_{\mathrm{G}}(\boldsymbol{\theta}) - \boldsymbol{\alpha}(\boldsymbol{\theta}) \equiv \boldsymbol{\varphi}(\boldsymbol{\theta}) - \boldsymbol{\alpha}(\boldsymbol{\theta})$$

Multiple solutions, i.e. images I, of a point source:

$$\boldsymbol{\theta}^{\mathrm{I}} = \boldsymbol{\varphi}^{-1}(\boldsymbol{\beta}_{\mathrm{S}})|_{\mathrm{I}}$$

Apparent (unlensed) angular motion:

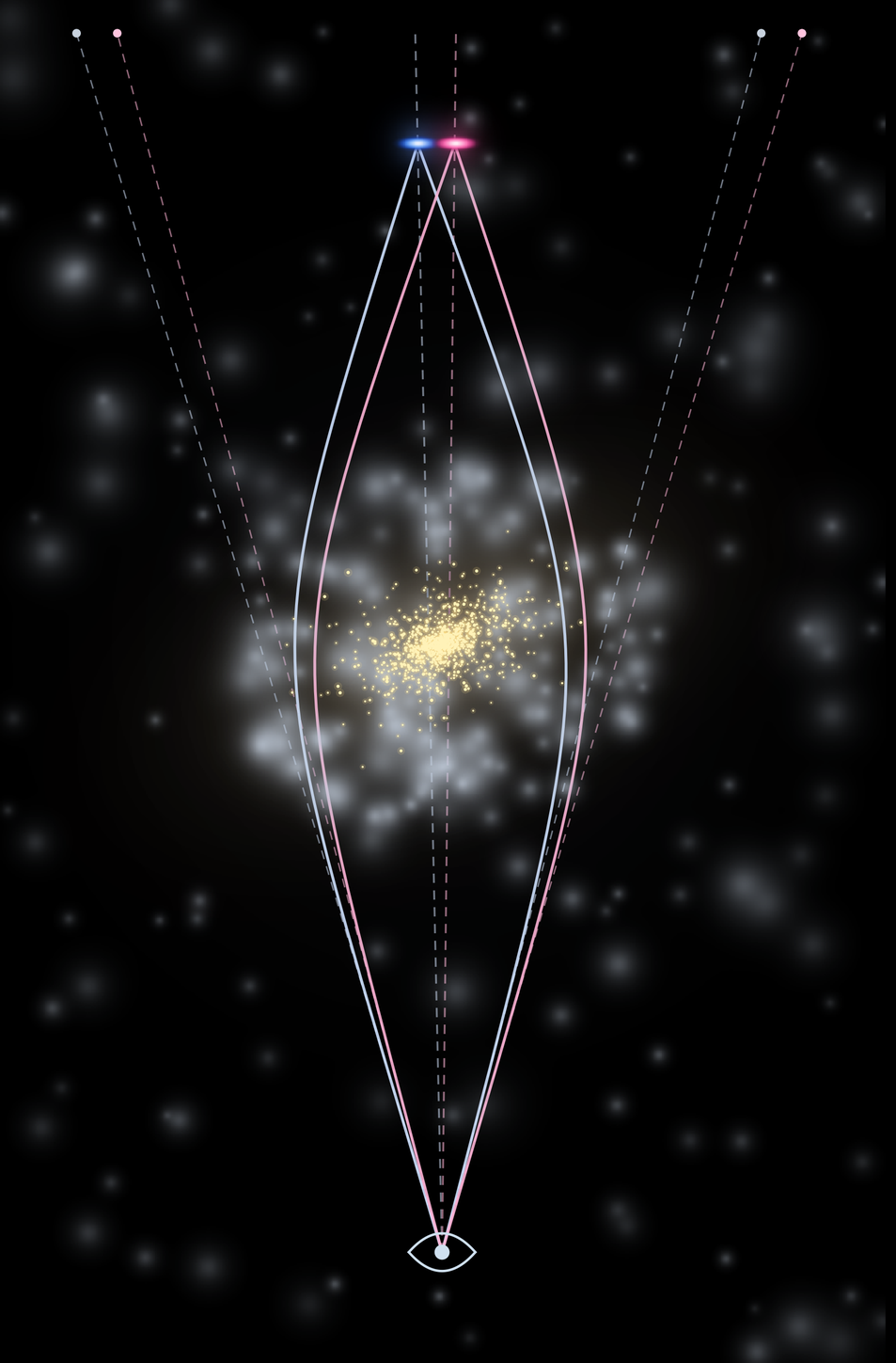
$$\boldsymbol{\mu} = \frac{\mathbf{v}_{\mathrm{S}}}{1+z_{\mathrm{S}}}\frac{1}{D_{\mathrm{S}}} - \frac{\mathbf{v}_{\mathrm{L}}}{1+z_{\mathrm{L}}}\frac{1}{D_{\mathrm{L}}} + \frac{\mathbf{v}_{\mathrm{o}}}{1+z_{\mathrm{L}}}\frac{D_{\mathrm{LS}}}{D_{\mathrm{L}}D_{\mathrm{S}}}$$

Angular trajectory of each image:

$$\theta_i^{\mathrm{I}}(t) - \theta_i^{\mathrm{I}}(t_0) = B_{ij}^{\mathrm{I}}\left\{\mu_j(t-t_0) + \alpha_j\left[\boldsymbol{\theta}^{\mathrm{I}}(t)\right] - \alpha_j\left[\boldsymbol{\theta}^{\mathrm{I}}(t_0)\right]\right\}$$

Magnifying distortion by inverse Jacobian:

$$B_{ij}^{\mathrm{I}} \equiv \left[A(\boldsymbol{\theta}^{\mathrm{I}})^{-1}\right]_{ij} \qquad A_{ij}(\boldsymbol{\theta}) \equiv \frac{\partial\varphi_i(\boldsymbol{\theta})}{\partial\theta_j}$$



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Stochastic, Weak, Astrometric Lensing

Two-point function for image centroid:

$$C^{\rm I}_{pq}(t) \equiv \langle \delta\theta^{\rm I}_p(t')\, \delta\theta^{\rm I}_q(t'+t)\rangle = B^{\rm I}_{pi} B^{\rm I}_{qj} \left\langle \alpha_i\big(\boldsymbol{\theta}^{\rm I}(t')\big)\, \alpha_j\big(\boldsymbol{\theta}^{\rm I}(t'+t)\big)\right\rangle$$

$$\equiv \int \frac{{\rm d}\omega}{2\pi}\, e^{-i\omega t}\, \widetilde{C}^{\rm I}_{pq}(\omega)$$

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$$\equiv \int \frac{{\rm d}\omega}{2\pi}\,e^{-i\omega t}\,\widetilde{C}^{\rm I}_{pq}(\omega)$$

Power spectral density:

[density fluctuations]→[gravitational potential fluctuations]→[lensing angle fluctuations]

$$\widetilde{C}^{\rm I}_{pq}(\omega) = B^{\rm I}_{pi}B^{\rm I}_{qj}\frac{4}{|\omega|}\int_0^{D_{\rm S}}{\rm d}D\left(\frac{D_{\rm S}-D}{D_{\rm S}}\right)^2(4\pi G\bar{\rho}a^2)^2\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\frac{{\rm d}\phi}{2\pi}\,\mathcal{M}_{ij}(\phi,\hat{\boldsymbol{\mu}}^{\rm I})\,P_\delta\left(\frac{|\omega|}{D\widetilde{\mu}^{\rm I}\cos(\phi)}\right)$$

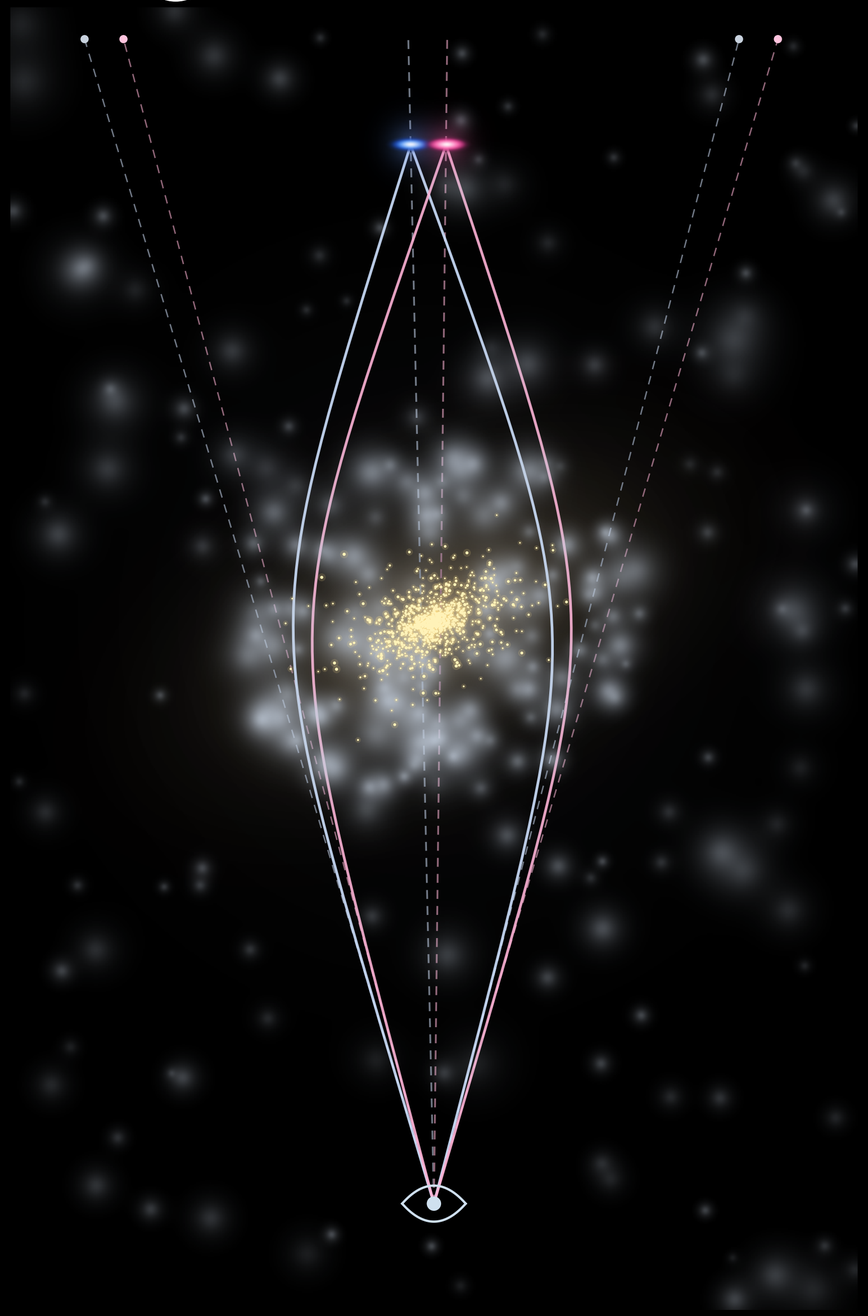
Stochastic, Weak, Astrometric Lensing from Halos

Single halo deflection:

$$\boldsymbol{\alpha}^{(1)}(\boldsymbol{\theta}) = \int \frac{\mathrm{d}^2 k}{(2\pi)^2}\, \widetilde{\boldsymbol{\alpha}}(\mathbf{k})\, e^{-i\mathbf{k}\cdot(\boldsymbol{\theta}-\boldsymbol{\theta}_\mathrm{L})}$$

$$\widetilde{\boldsymbol{\alpha}}(\mathbf{k}) = \frac{D_\mathrm{LS}}{D_\mathrm{L} D_\mathrm{S}}\, 4GM_\mathrm{L}\, \frac{2\pi i}{k}\, \hat{\mathbf{k}}\, F(k\gamma_\mathrm{L})$$

$$F(k\gamma_\mathrm{L}) = \int_0^\infty \mathrm{d}x\, J_1(x)\, M_\mathrm{L}^{-1} M\left(\frac{x r_\mathrm{L}}{k\gamma_\mathrm{L}}\right)$$



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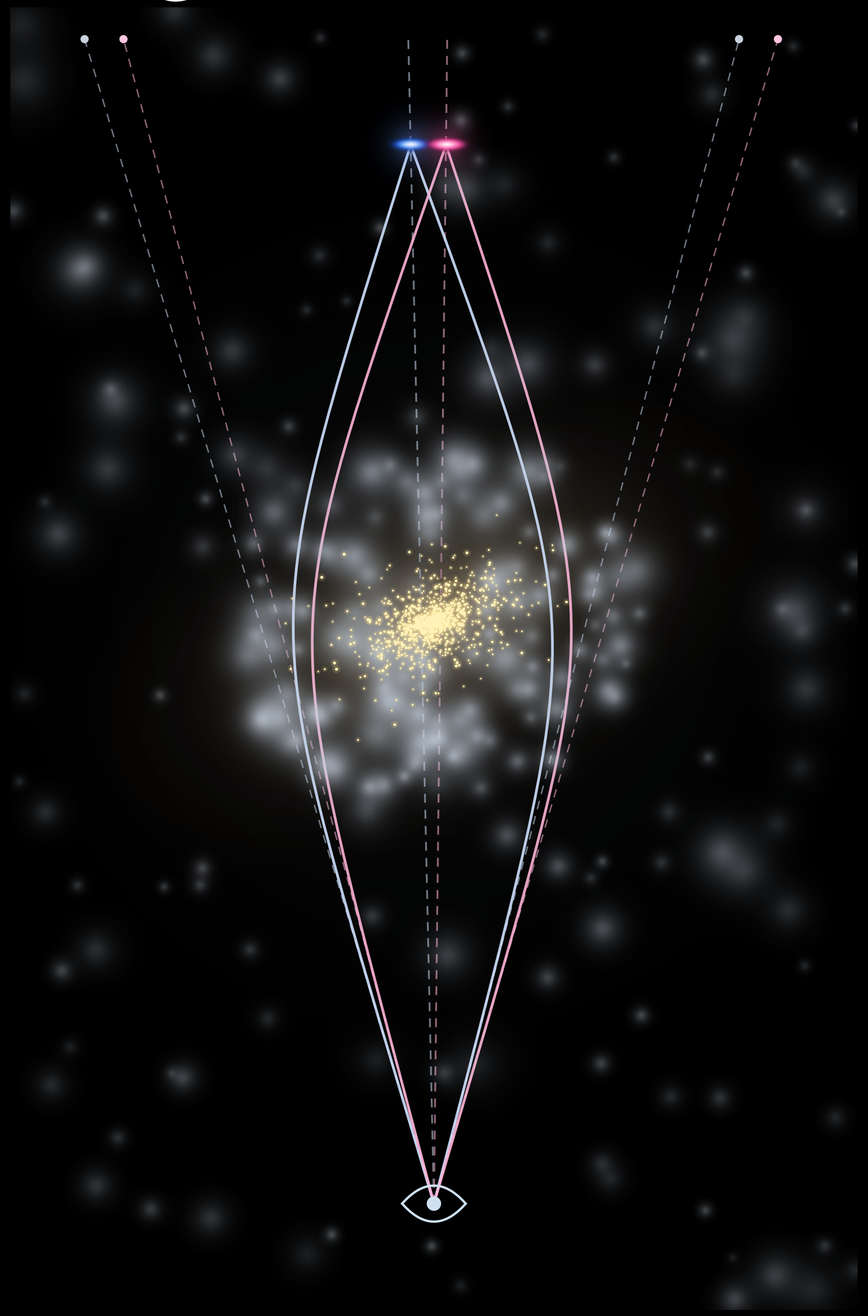
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Incoherent, random-walk deflections:

$$\left\langle \alpha_i(\boldsymbol{\theta})\, \alpha_j(\boldsymbol{\theta}') \right\rangle = \int \mathrm{d}D_\mathrm{L}\, D_\mathrm{L}^2 \int \mathrm{d}^2\theta_\mathrm{L}\, n_\mathrm{L}\, \alpha_i^{(1)}(\boldsymbol{\theta})\, \alpha_j^{(1)}(\boldsymbol{\theta}')$$



Stochastic, Weak, Astrometric Lensing from Halos

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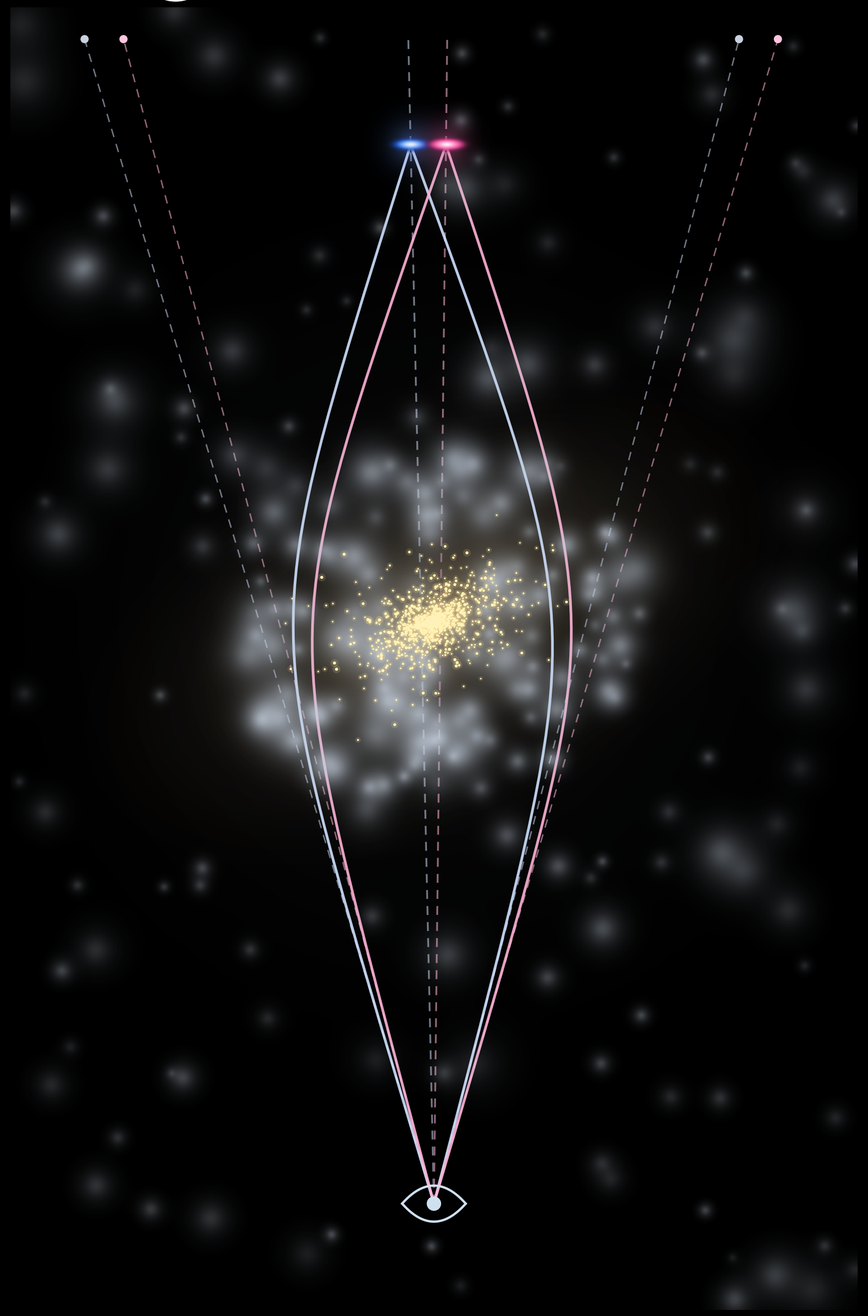
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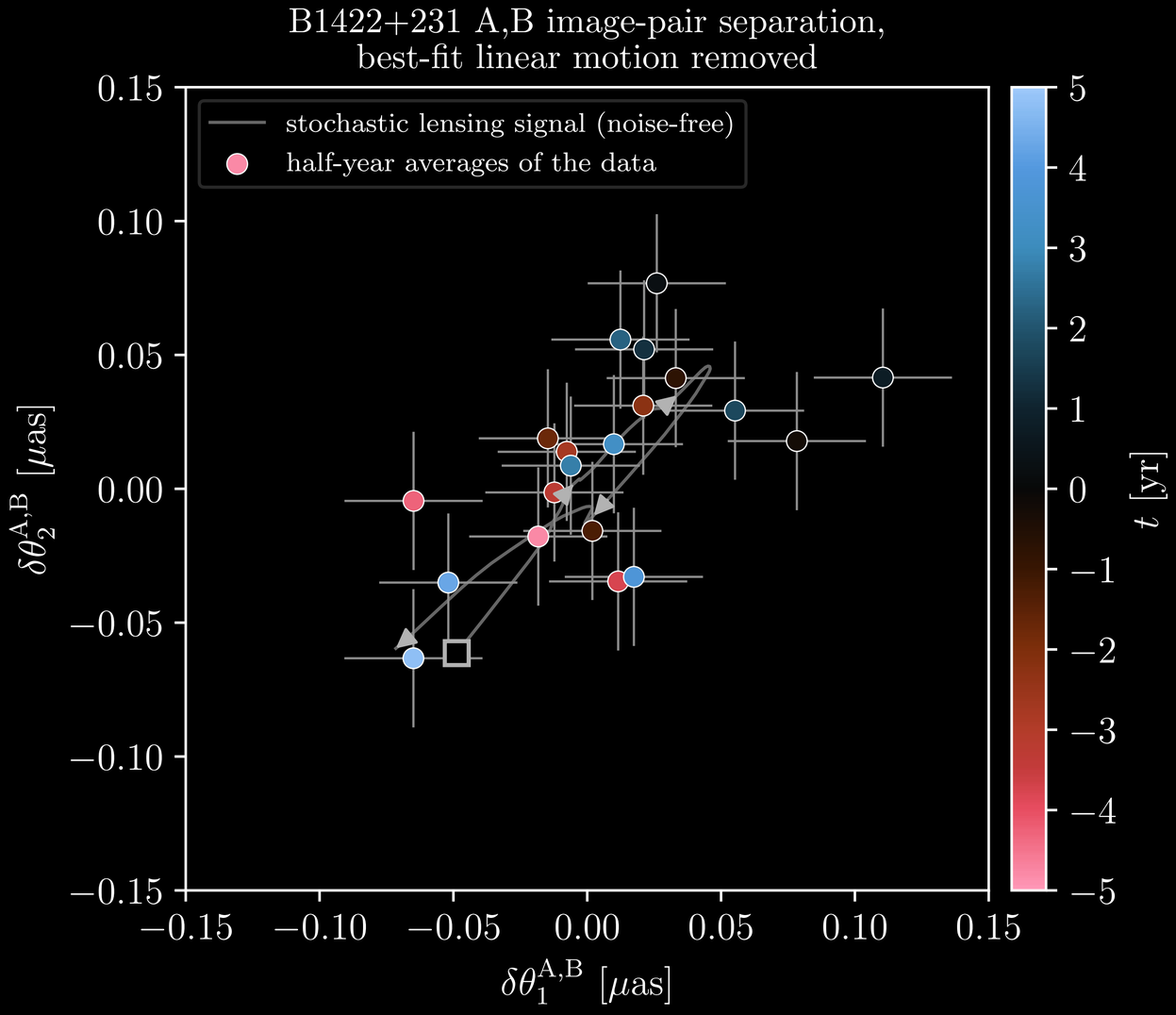
Power spectral density:

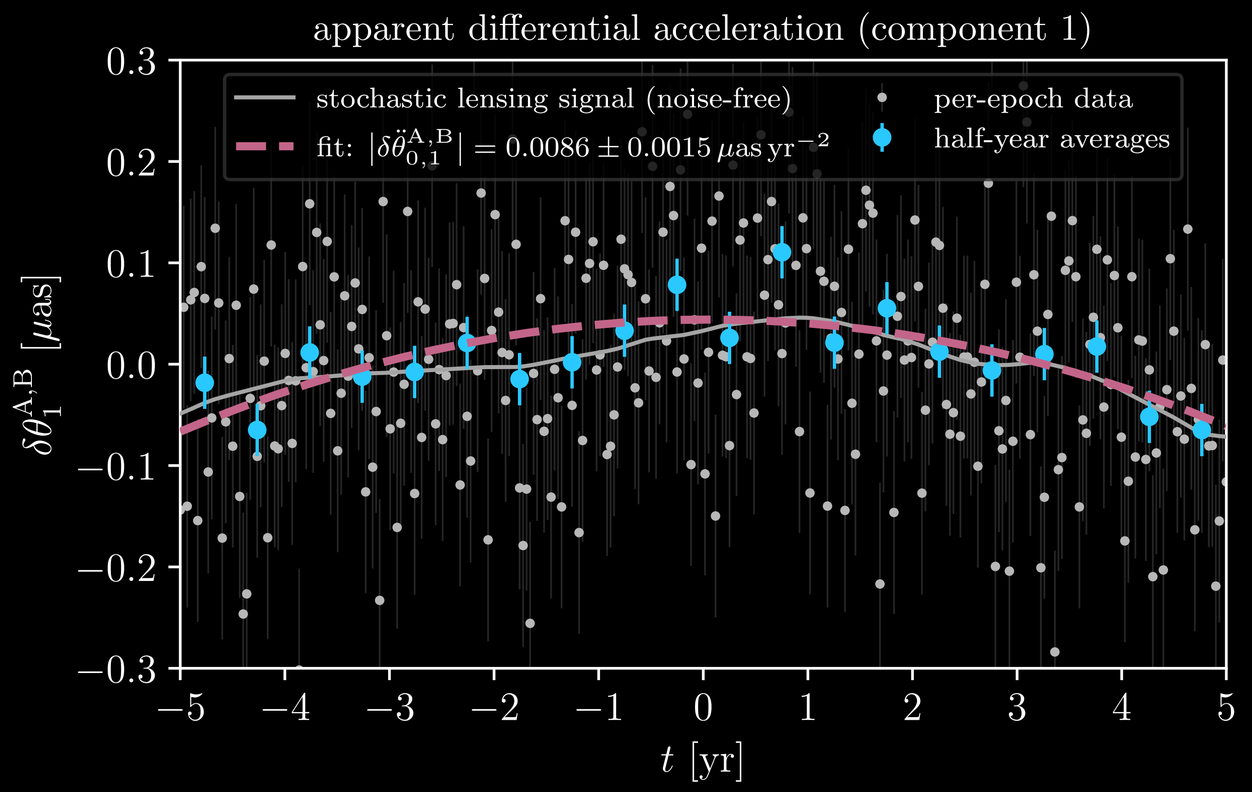
$$\widetilde{C}^\mathrm{I}_{pq}(\omega) = B^\mathrm{I}_{pi} B^\mathrm{I}_{qj}\, \frac{\kappa^\mathrm{I}_\mathrm{L}\, \theta^2_\mathrm{E,L}}{|\omega|} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \mathrm{d}\phi\, Q^\mathrm{I}_{ij}\, F\left[\frac{|\omega|\gamma_\mathrm{L}}{\widetilde{\mu}^\mathrm{I} c_\phi}\right]^2$$

$$Q^\mathrm{I} \equiv \begin{pmatrix} 1 + c_{2\zeta^\mathrm{I}}\, c_{2\phi} & s_{2\zeta^\mathrm{I}}\, c_{2\phi} \\ s_{2\zeta^\mathrm{I}}\, c_{2\phi} & 1 - c_{2\zeta^\mathrm{I}}\, c_{2\phi} \end{pmatrix}$$

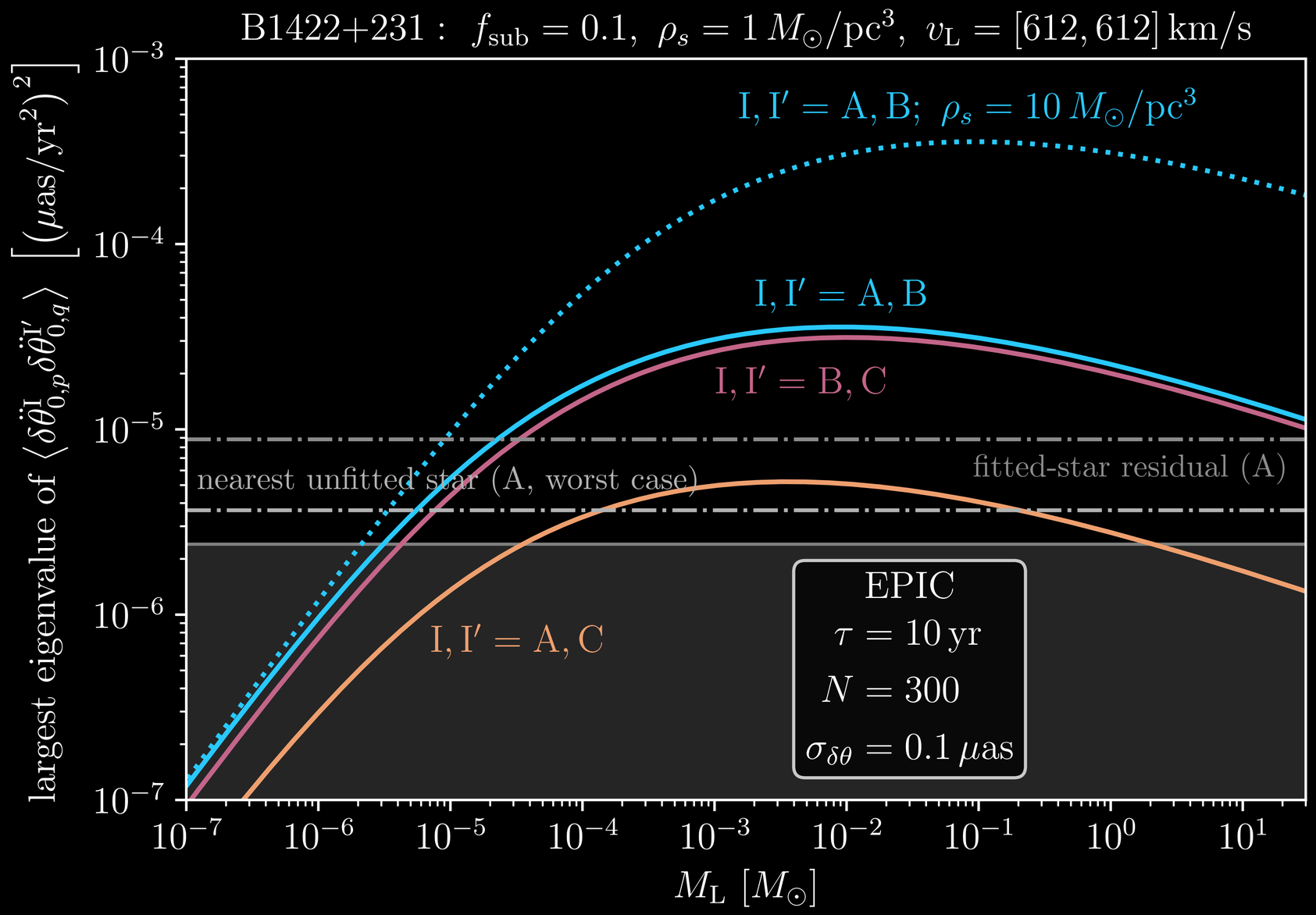


Stochastic Astrometric Lensing

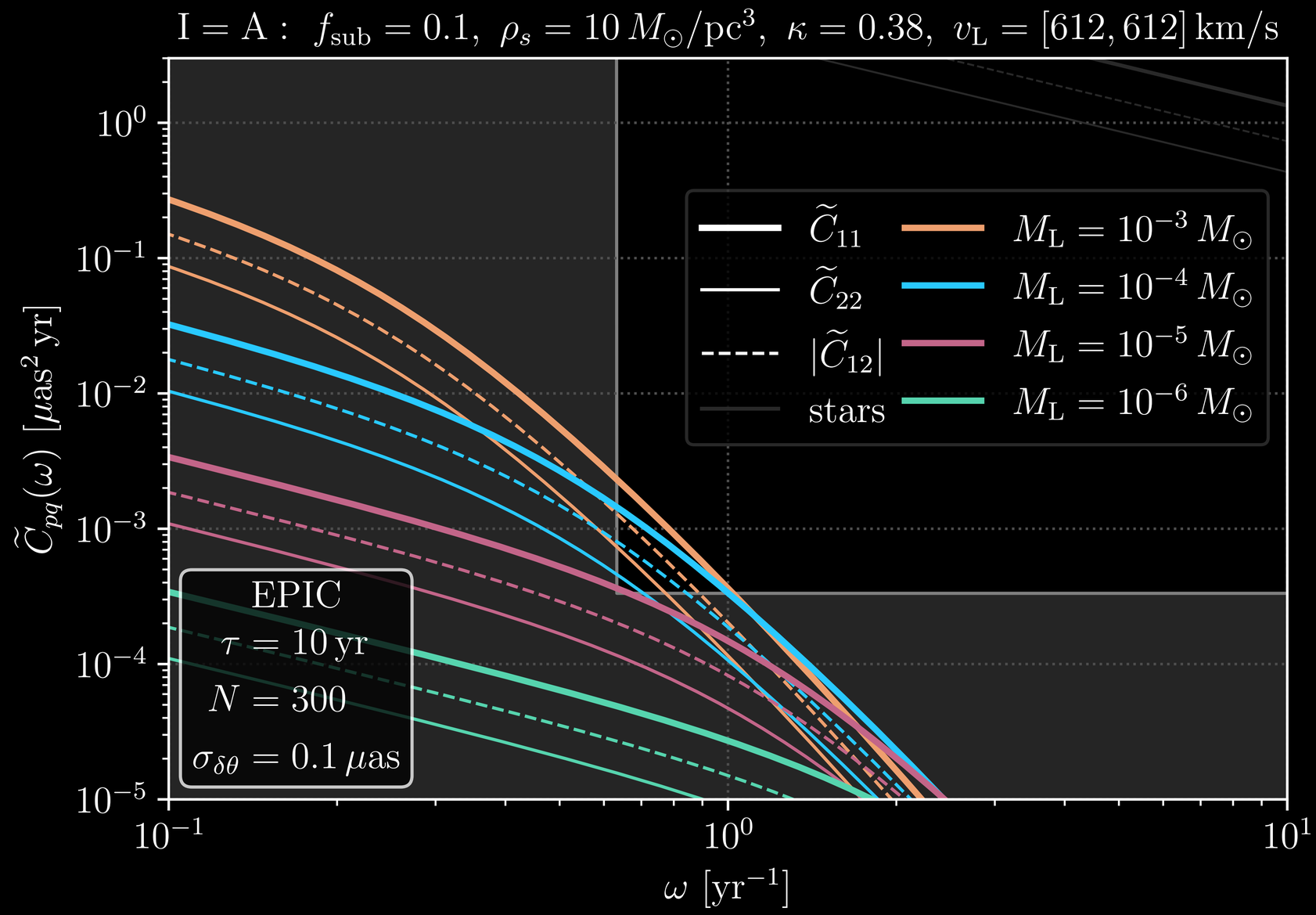




Lensing-induced Acceleration



Lensing-induced Stochastic Noise



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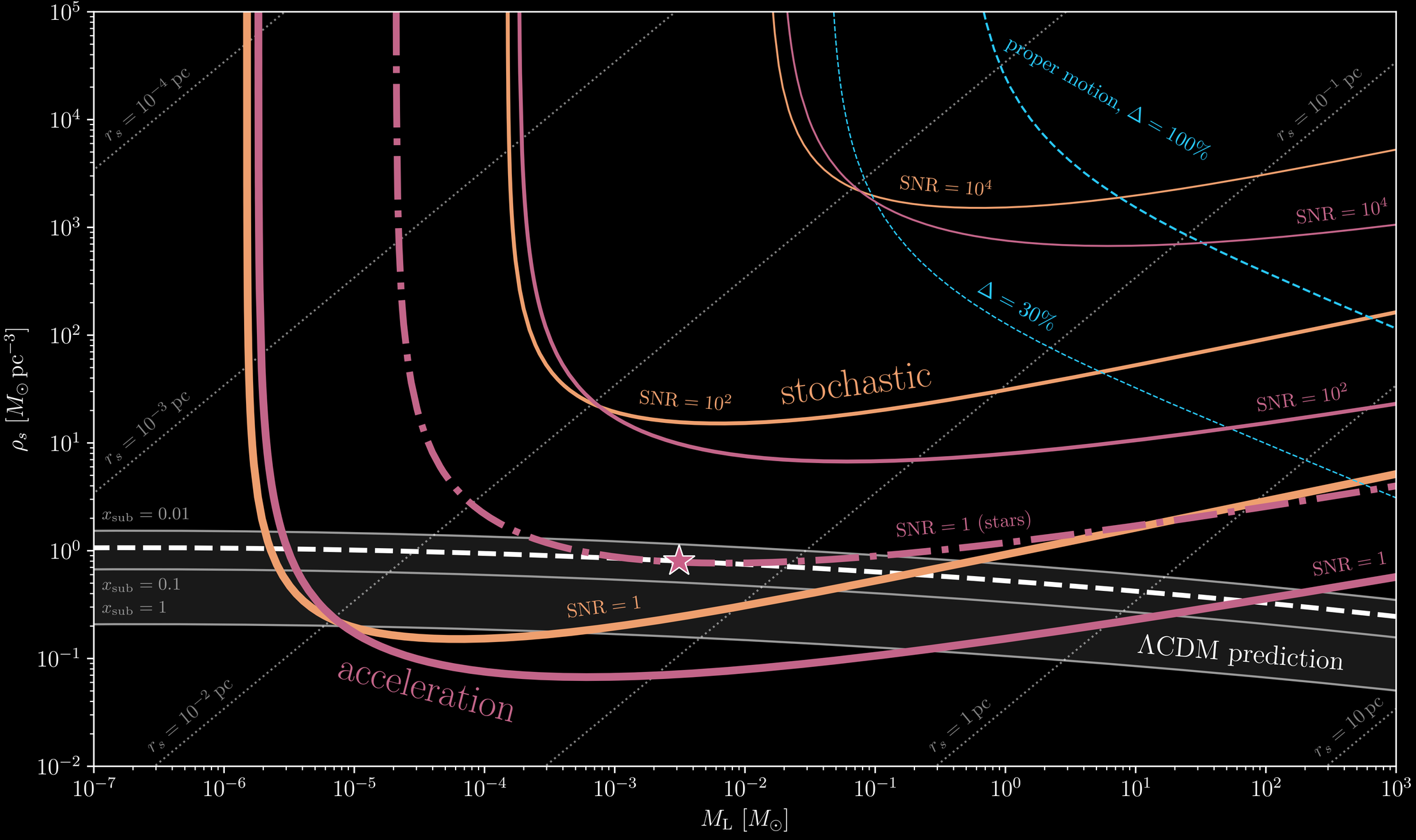
Astrometric Observables

Time-series data: $\boldsymbol{\theta}^{\rm I}(t_1),\ \boldsymbol{\theta}^{\rm I}(t_2),\ \ldots,\ \boldsymbol{\theta}^{\rm I}(t_N)$ with std $\sigma_{\delta\theta}$

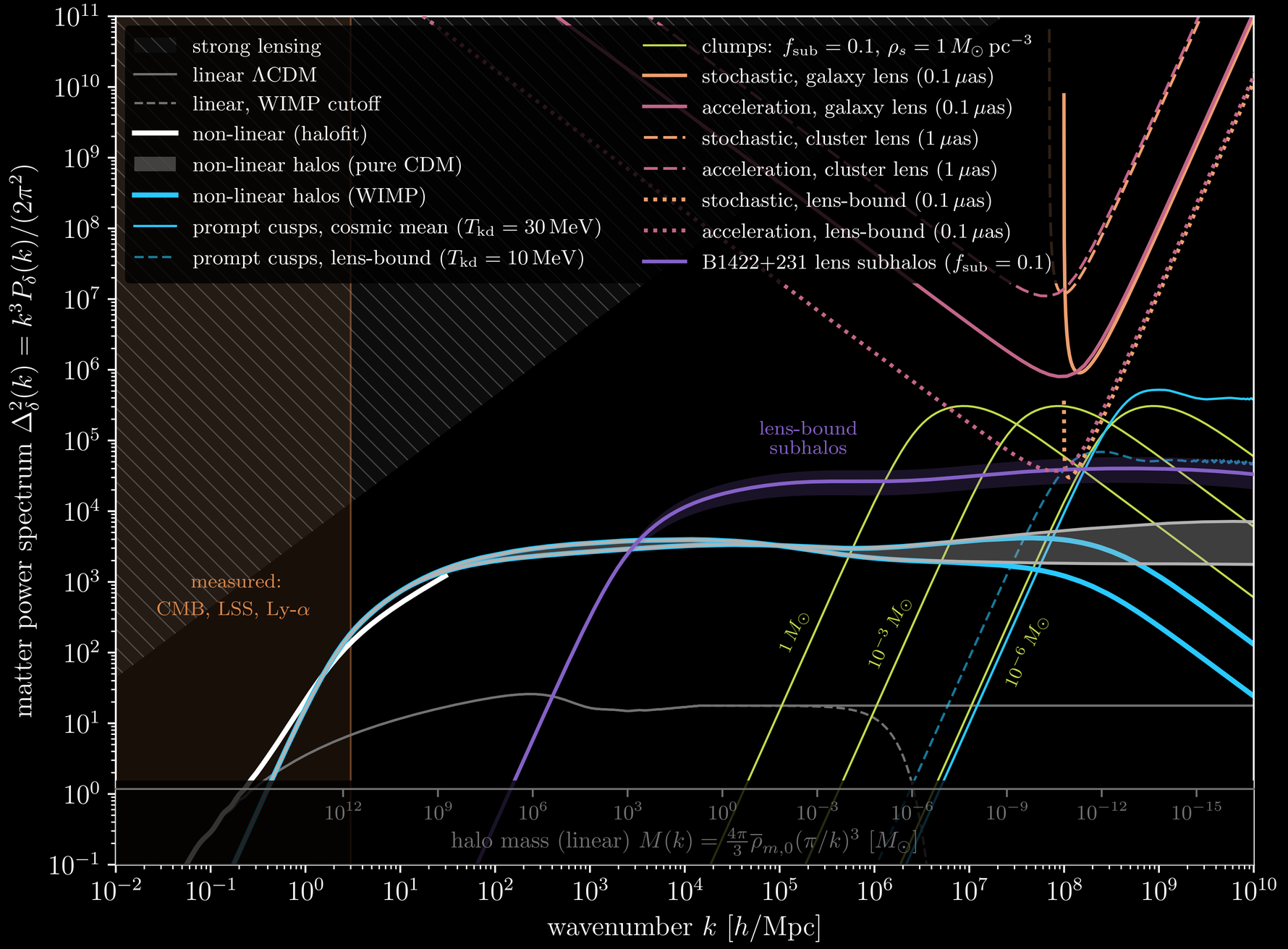
Fourier power: calculate DFT at freqs $\omega_n = 2\pi n/\tau$ with $\tau \equiv t_N - t_1$

Acceleration: fit $\theta_i^{\rm I}(t) = \theta_{0,i}^{\rm I} + \dot{\theta}_{0,i}^{\rm I} t + \ddot{\theta}_{0,i}^{\rm I} t^2/2 + \mathcal{O}(t^3)$

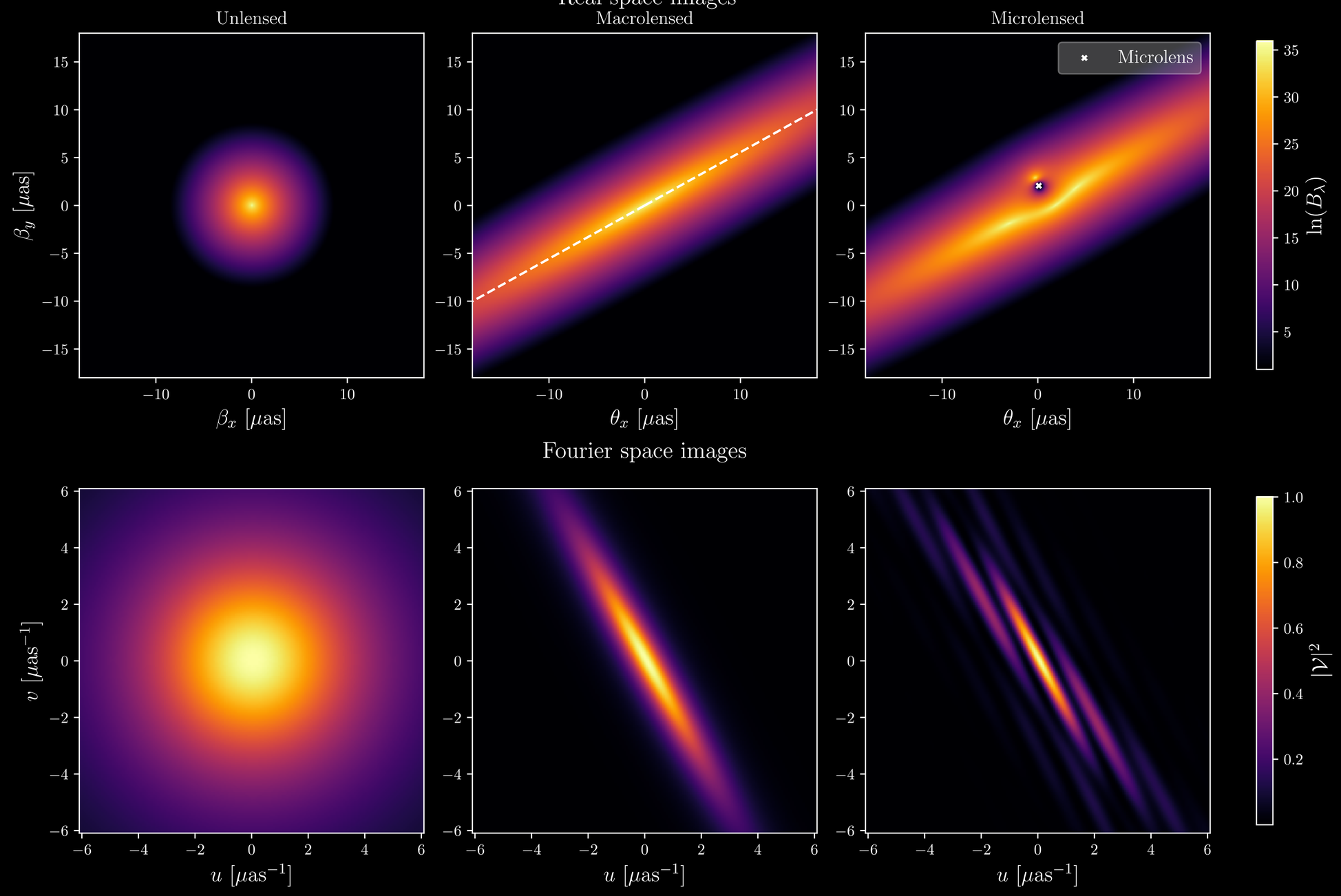
Halo Spectrum Sensitivity



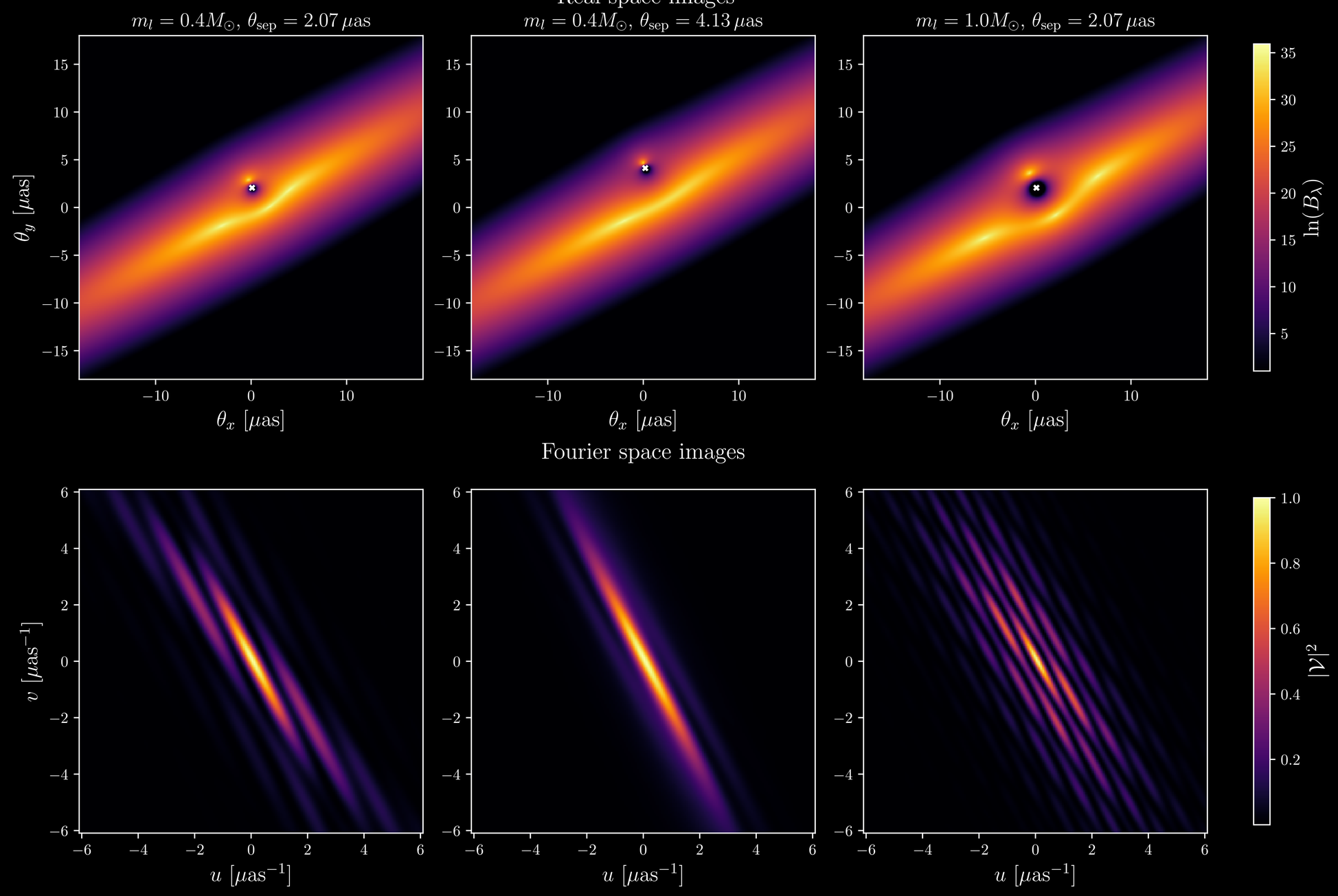
Non-linear Matter Power Spectrum Sensitivity



Stellar Microlensing Background



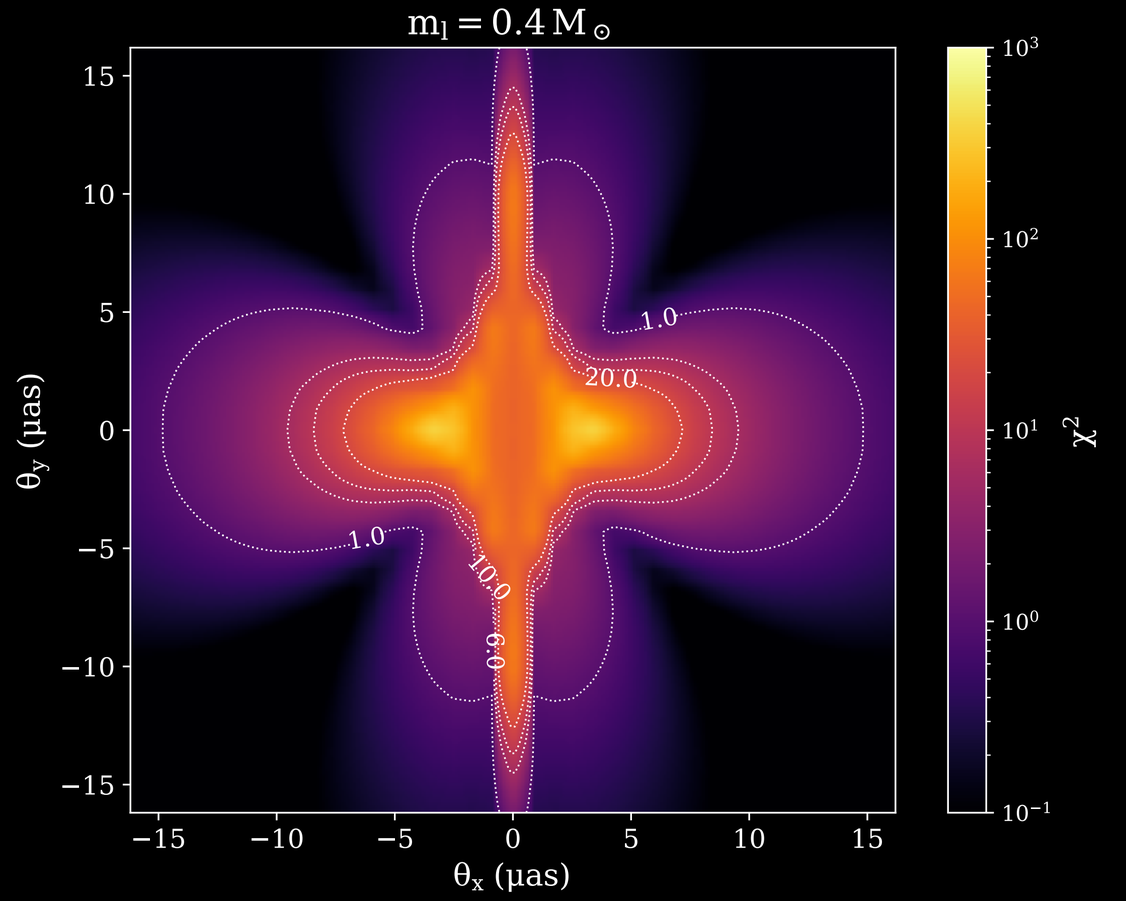
Stellar Microlensing Background



Stellar Microlensing Background

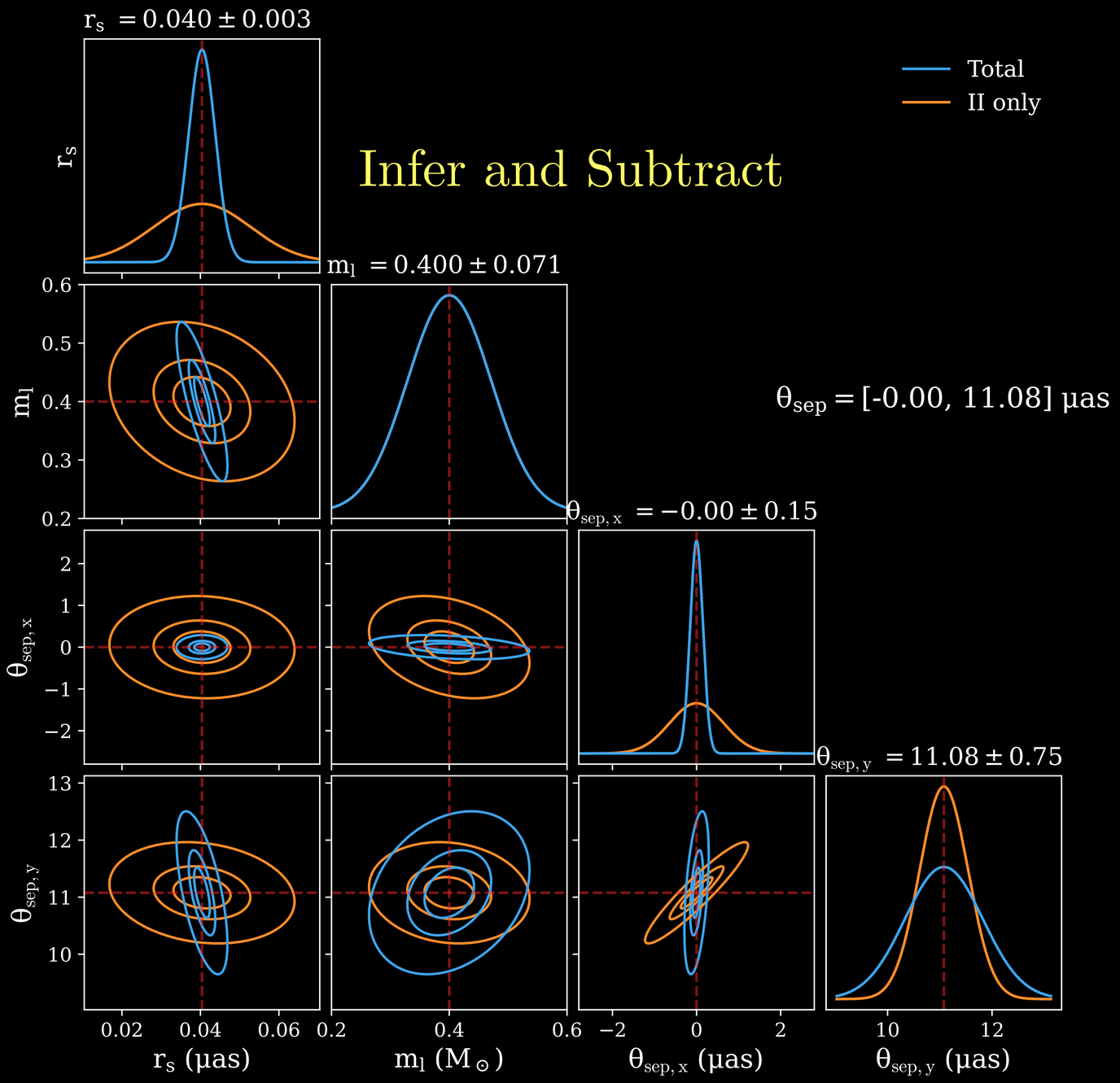
Stellar Microlensing Background

Detect or Certify

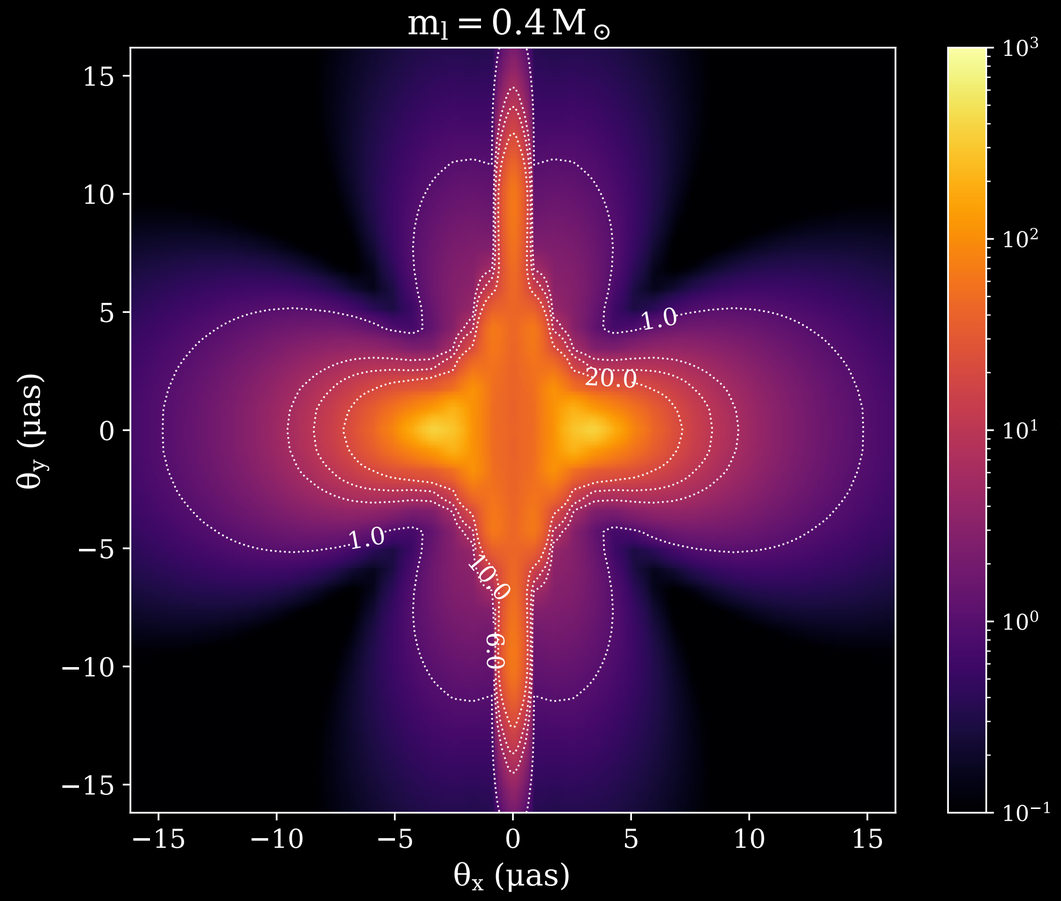


Stellar Microlensing Background

Infer and Subtract



Detect or Certify



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5. Future Data

   Intensity interferometry + EPIC

[KVT, D.E. Kaplan; 2608.27557]

[A. Moran, KVT; 2608.27577]

[KVT, M. Baryakhtar, M. Galanis, N. Weiner; arXiv:2307.03221]

[M. Galanis, KVT, M. Baryakhtar, N. Weiner; arXiv:2307.06989]

Outline

1. Motivation

   Small-scale structure as a probe of DM microphysics and primordial curvature

2. Signature

   Excess time-dependent astrometric lensing noise, magnified in multiply imaged quasars

3. Sensitivity Forecast

   Acceleration and stochastic observables; instrumental, intrinsic, stellar backgrounds

~~4. Existing Data~~

   Amplitude interferometry, *Gaia* DR3, *HST*, *JWST*

5. Future Data

   Intensity interferometry + EPIC

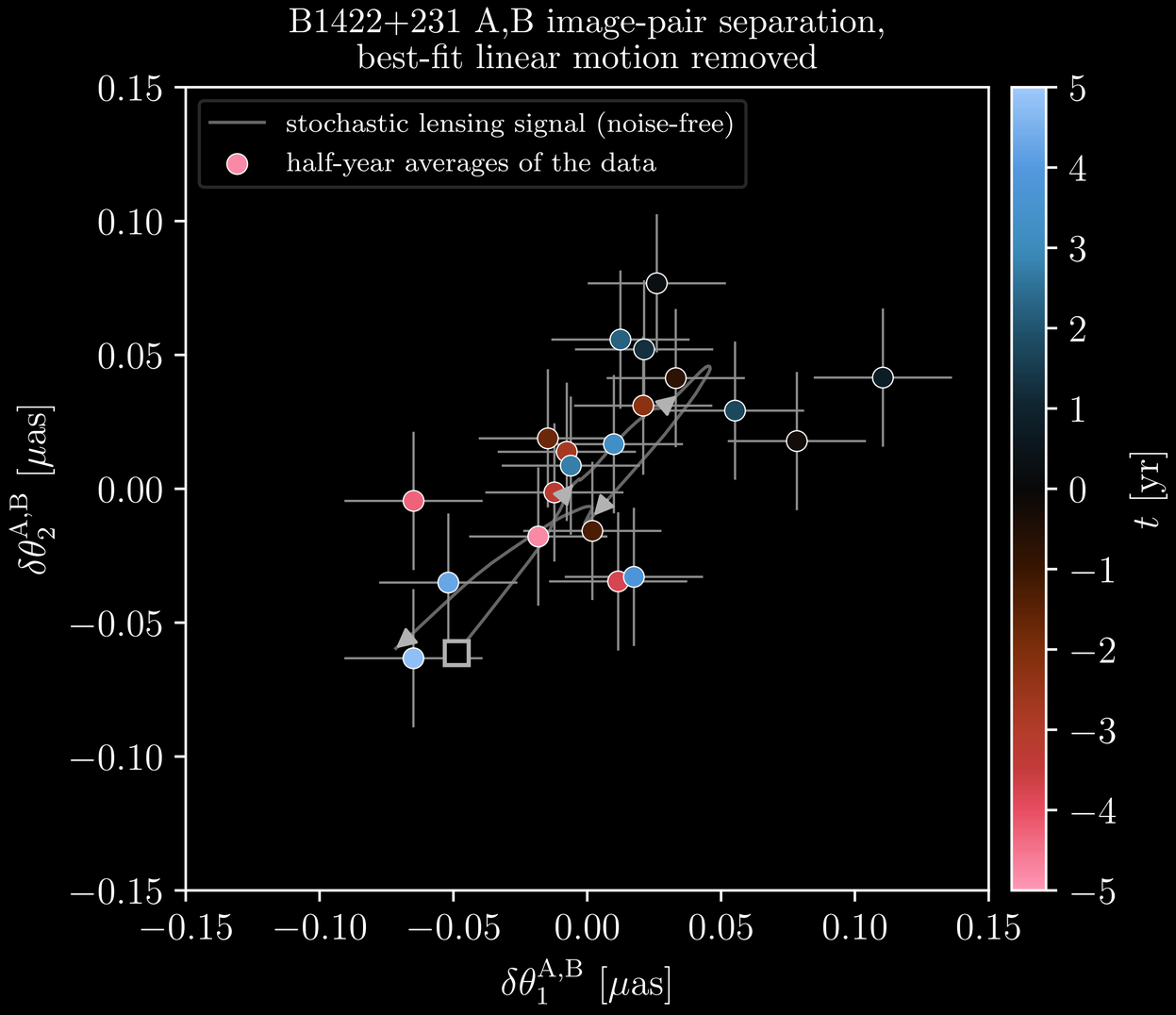
[KVT, D.E. Kaplan; 2608.27557]

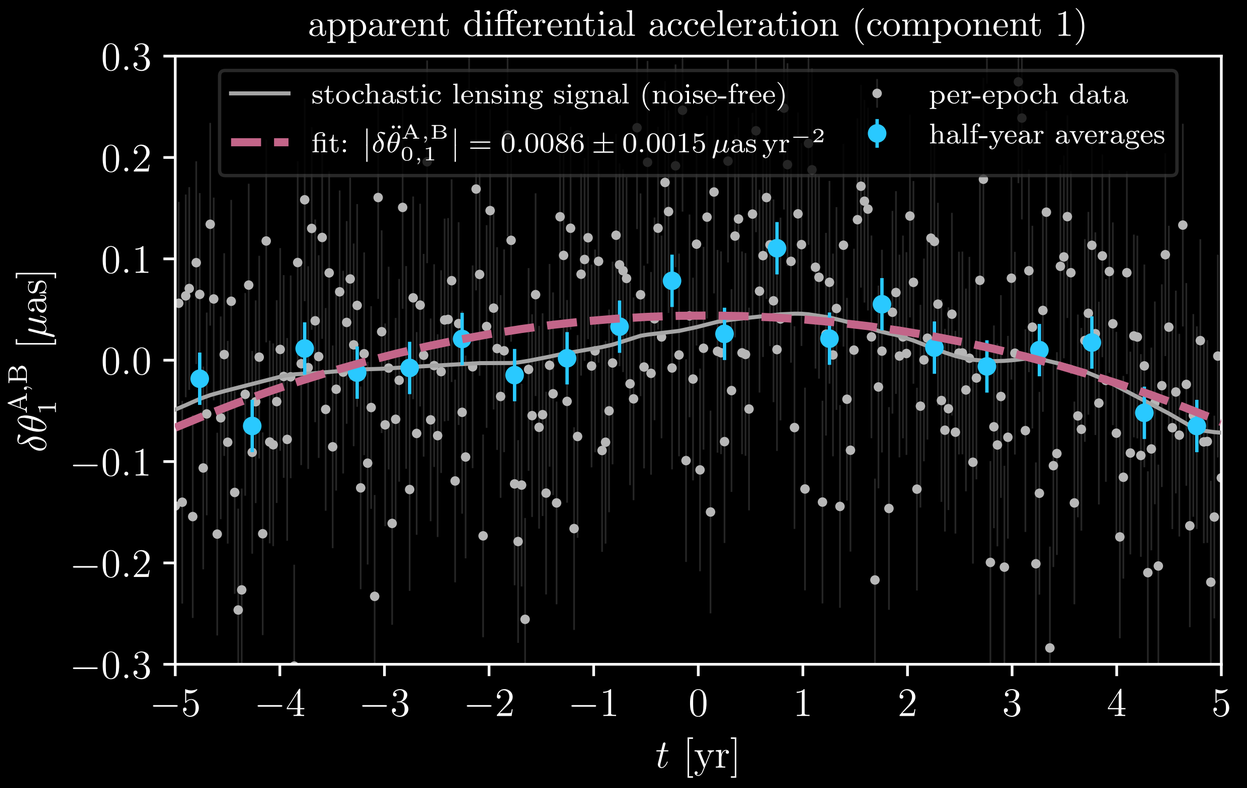
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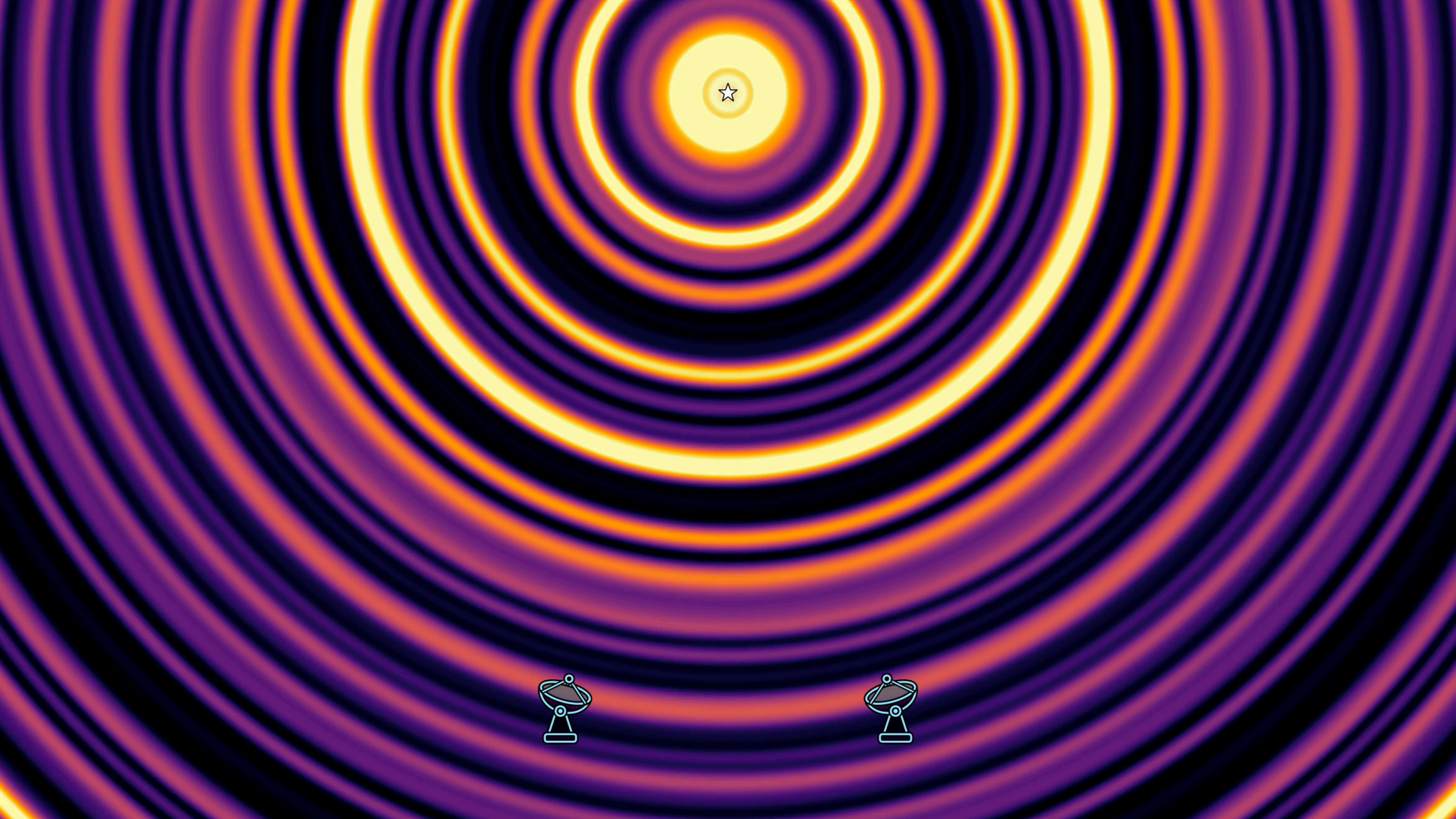
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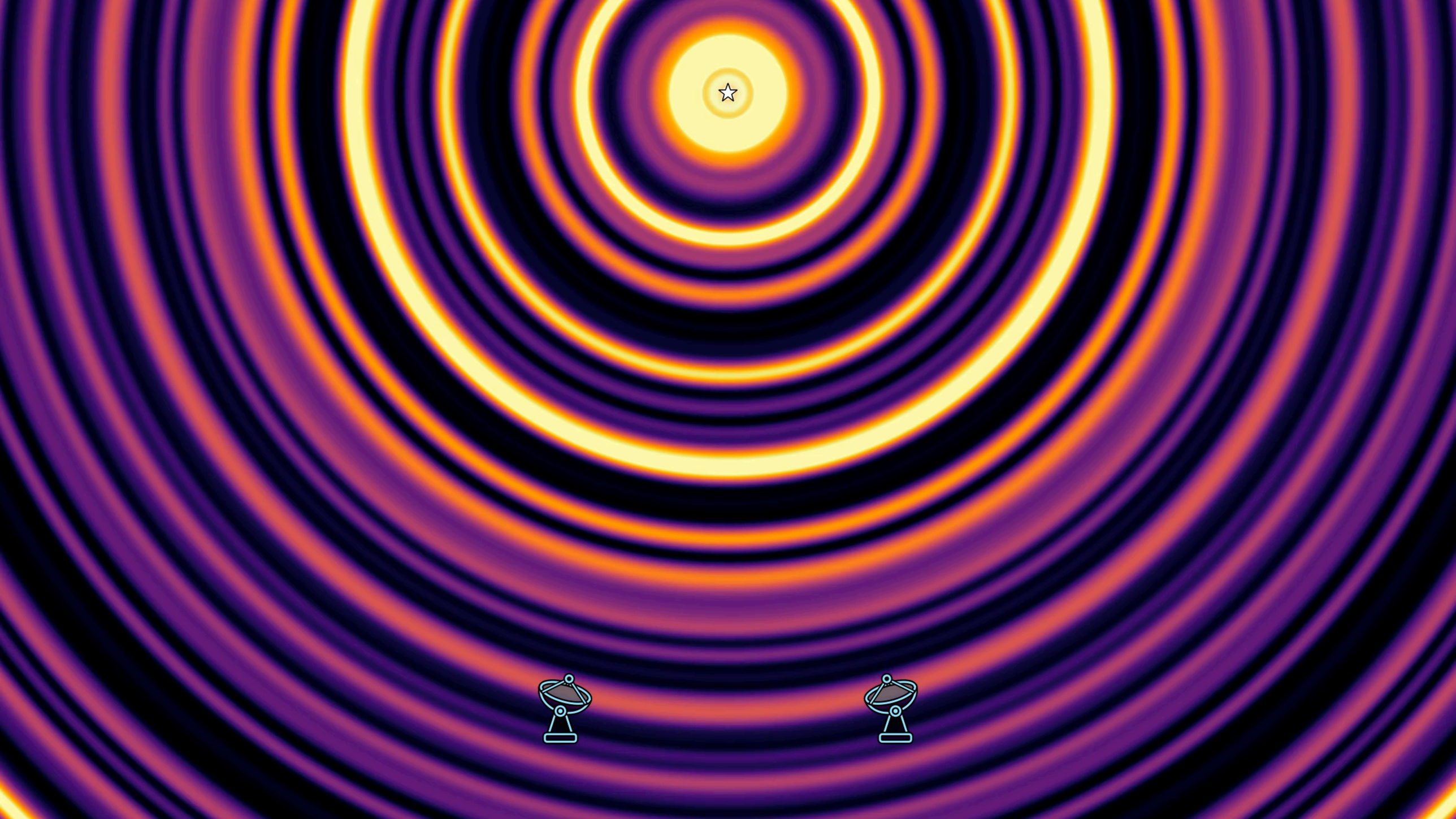
[M. Galanis, KVT, M. Baryakhtar, N. Weiner; arXiv:2307.06989]

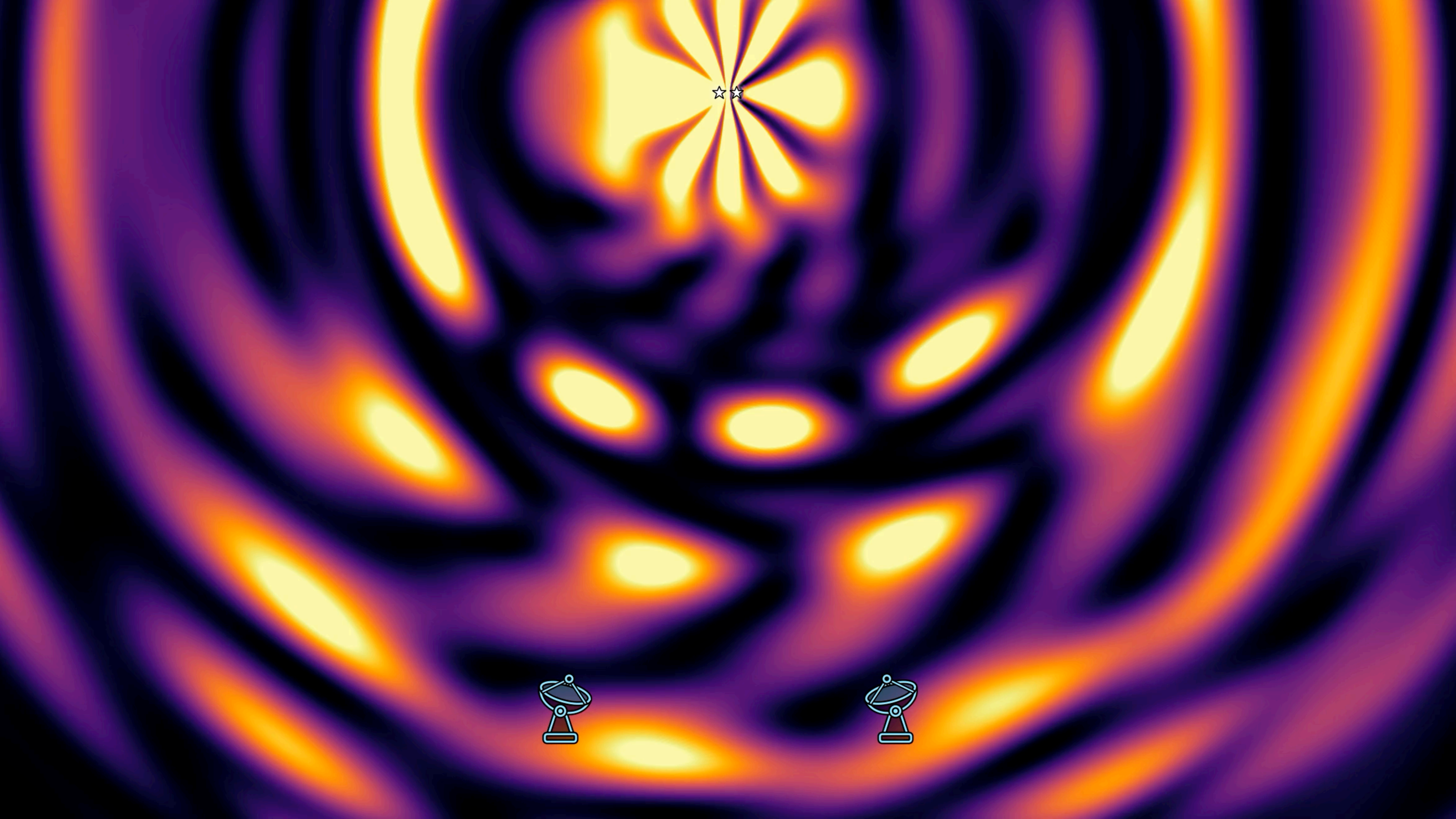
How to get sub-microarcsecond precision?

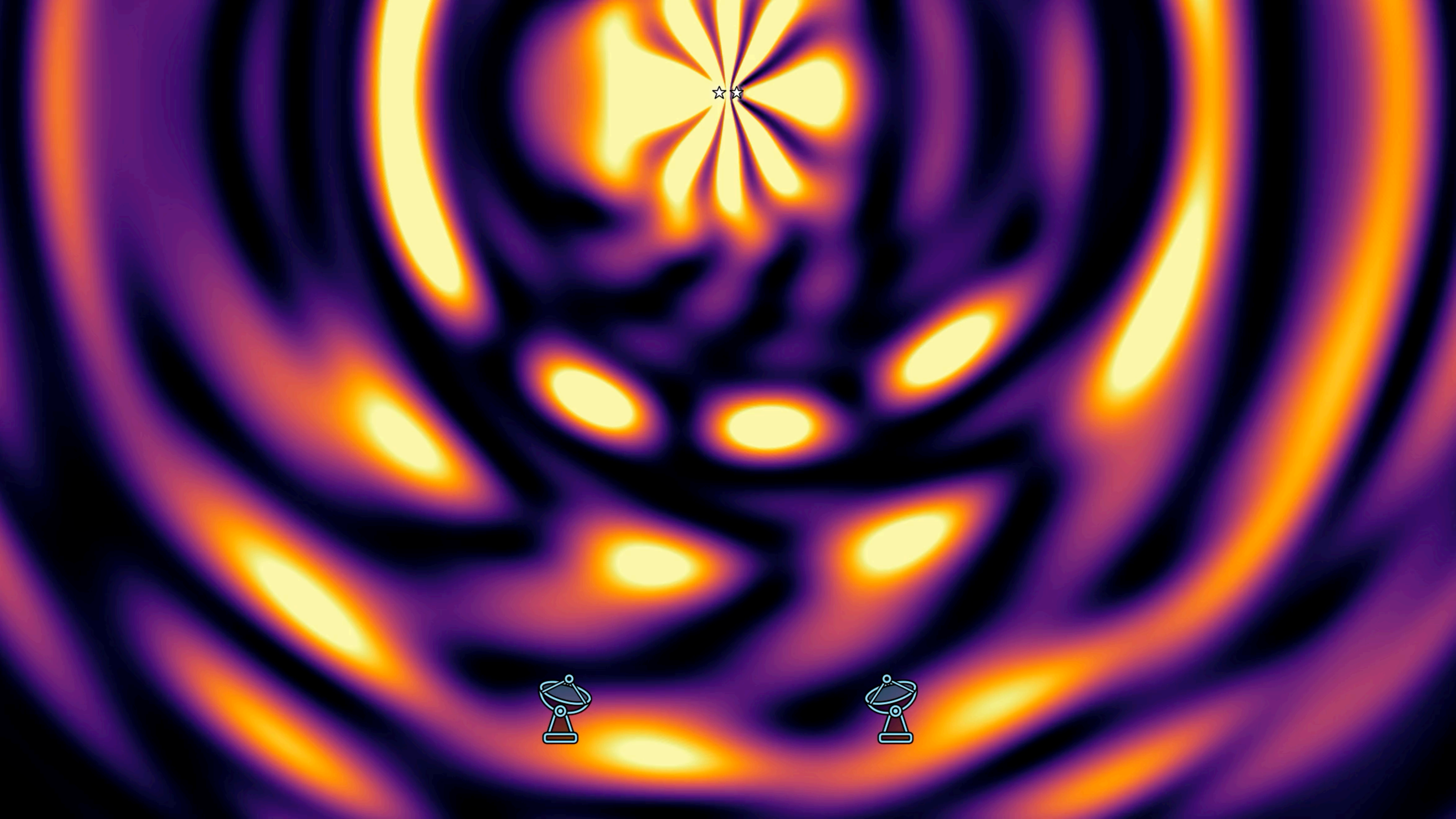


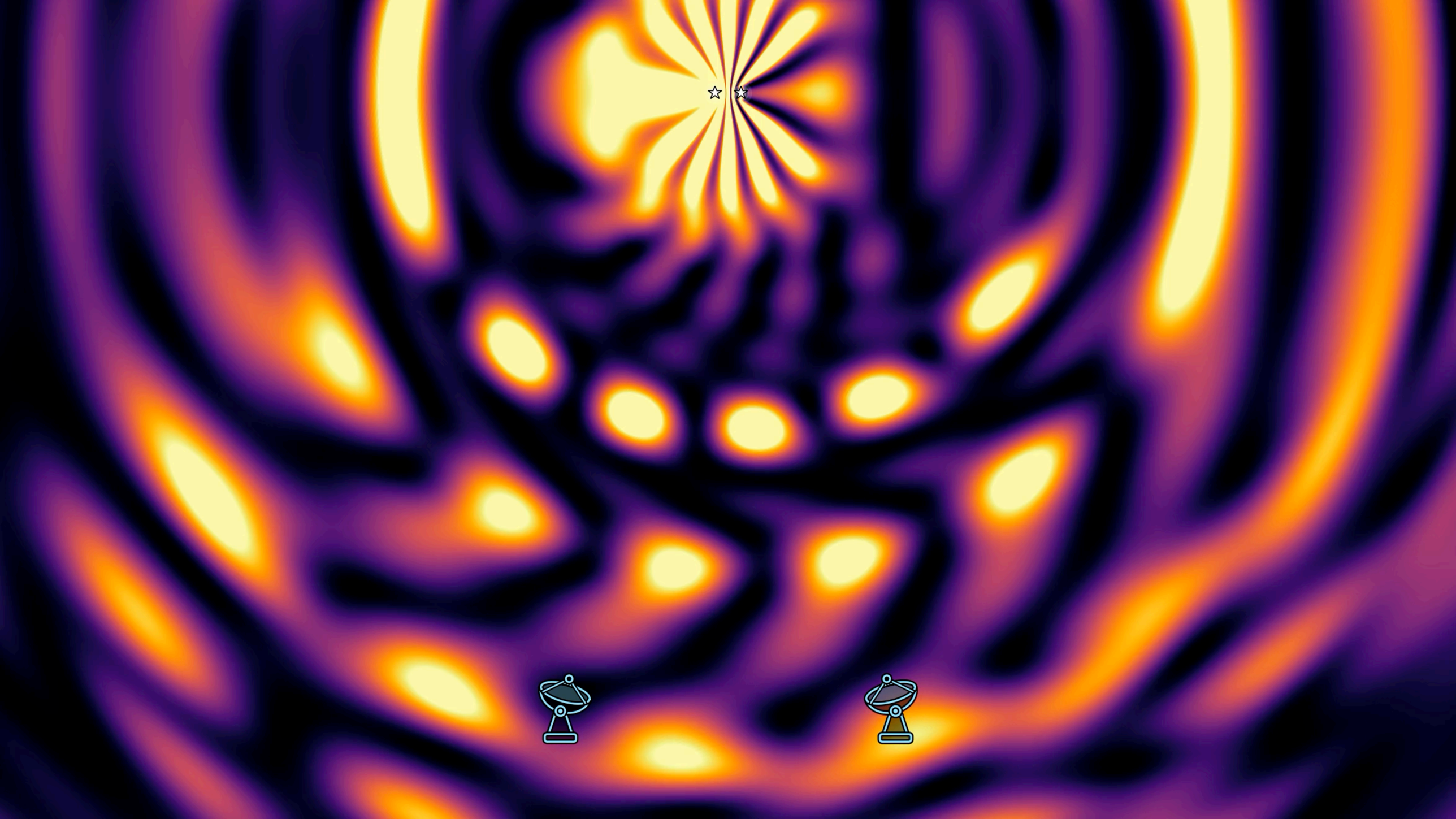


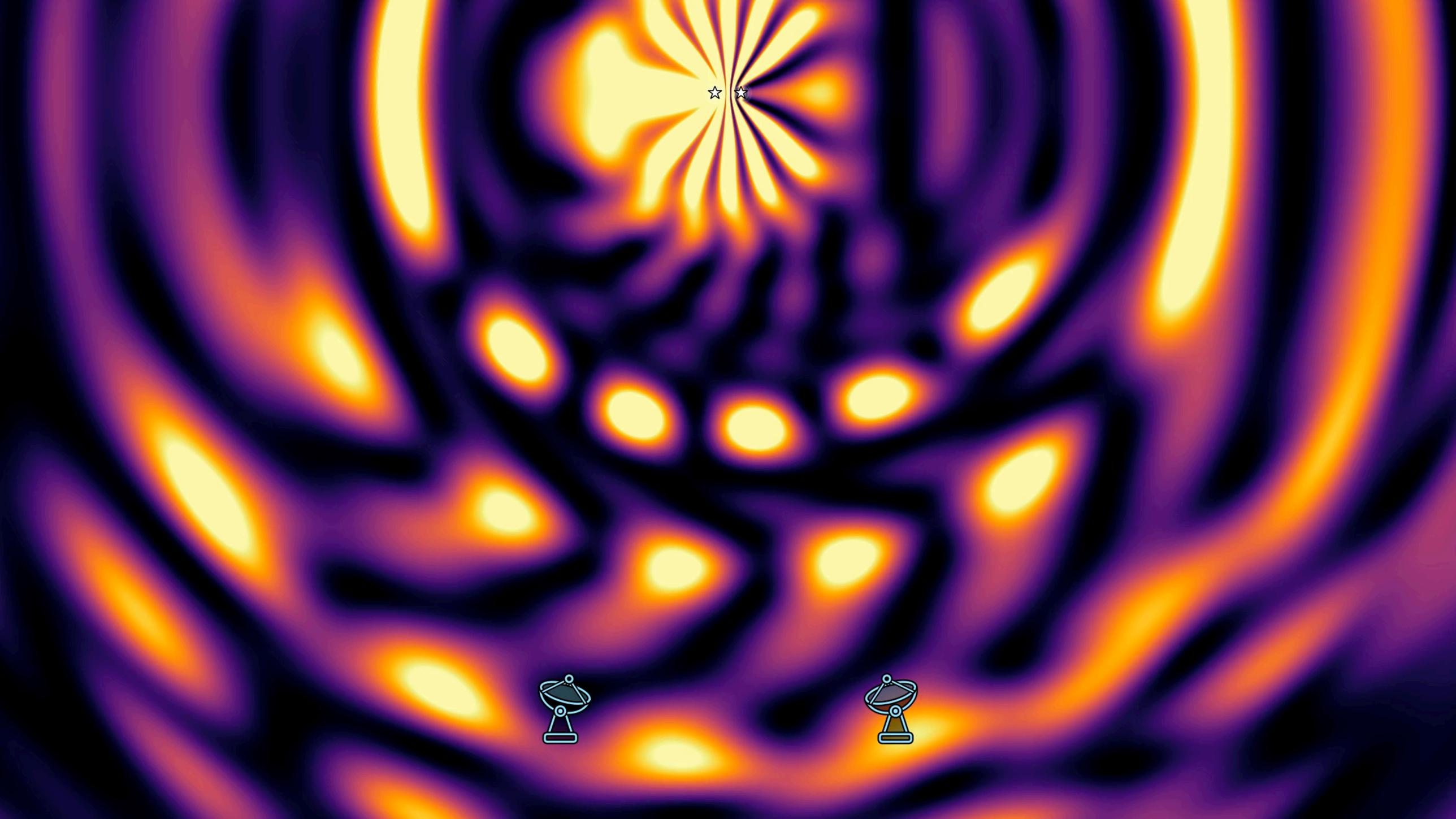


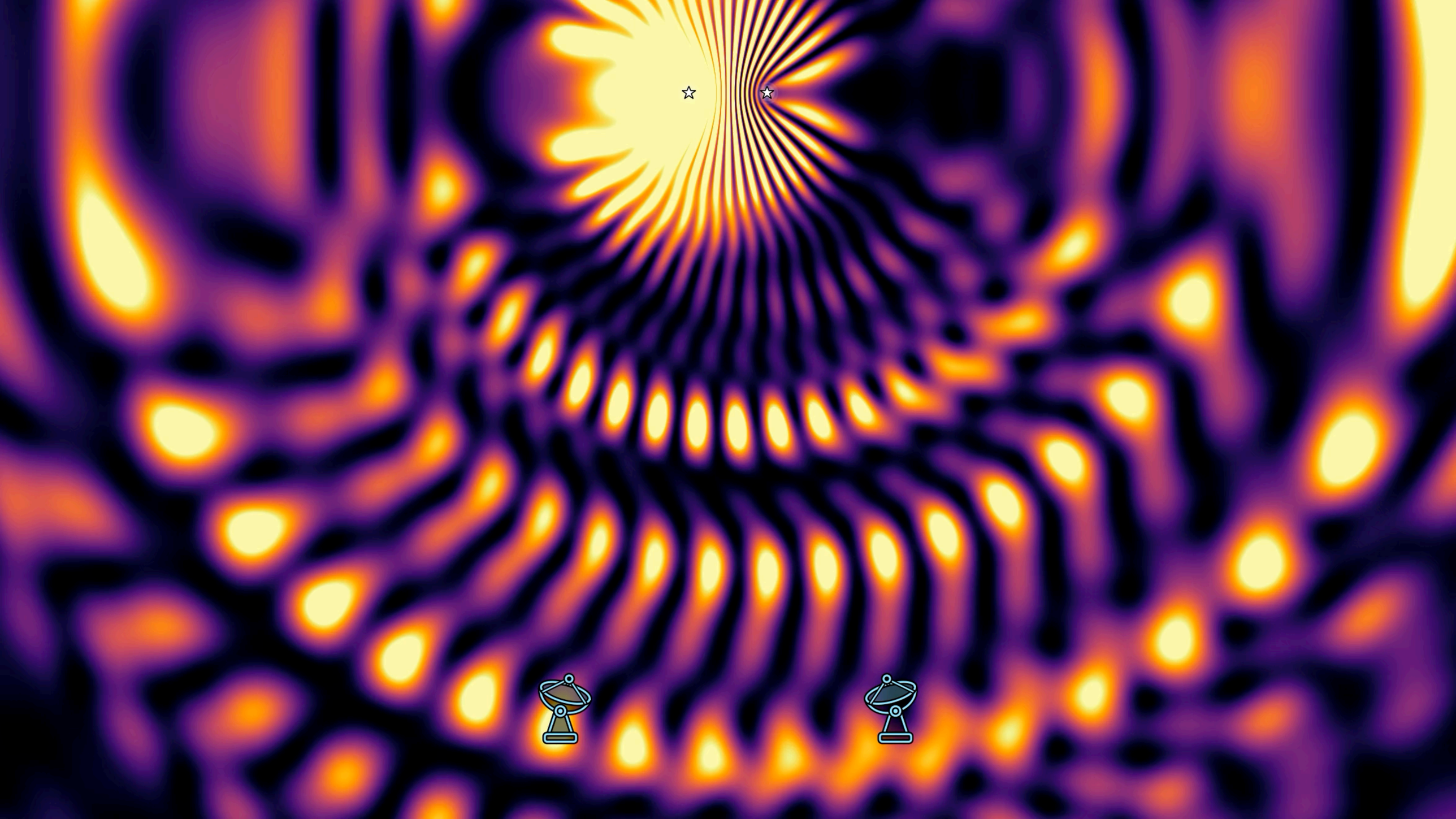


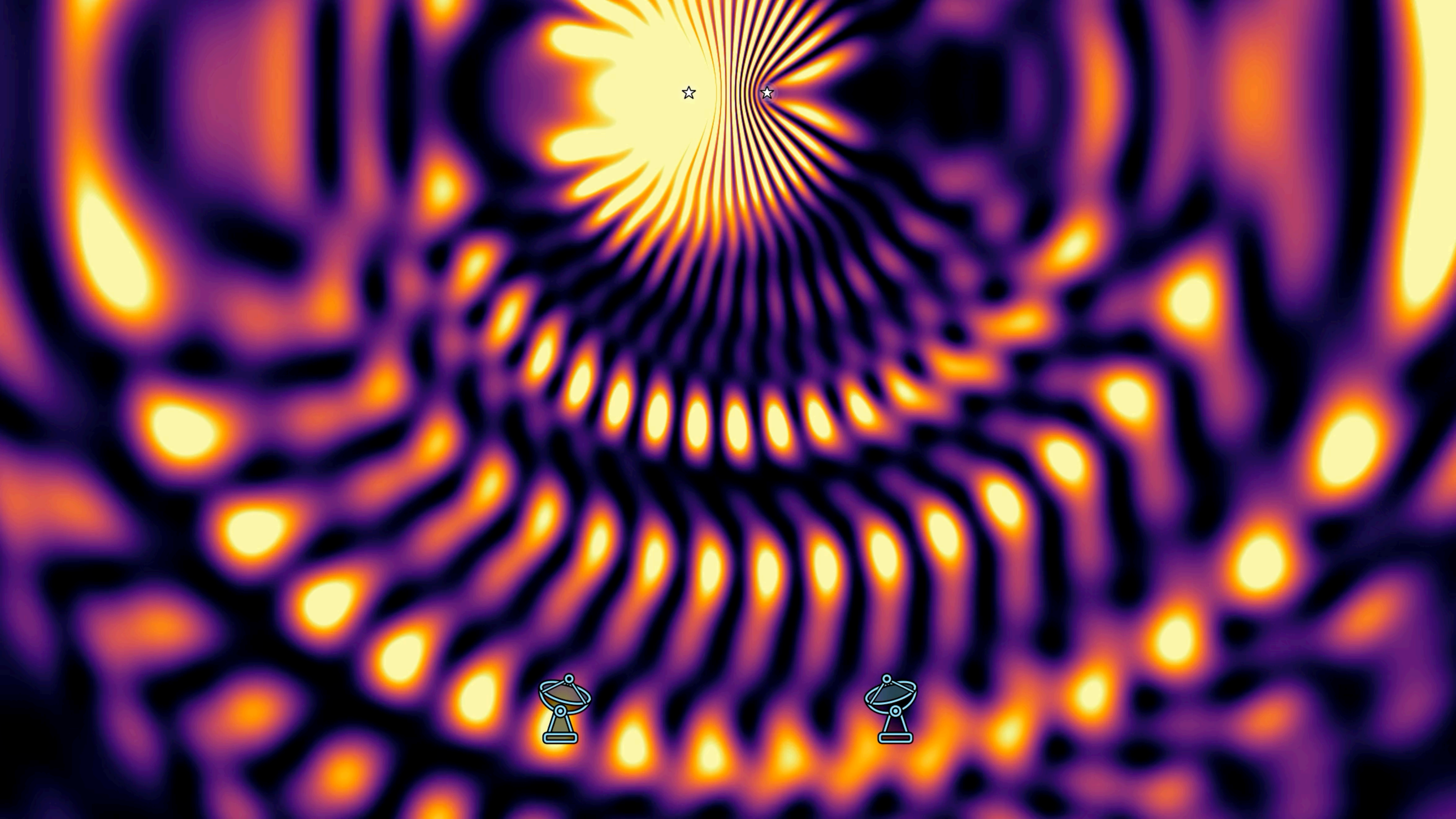


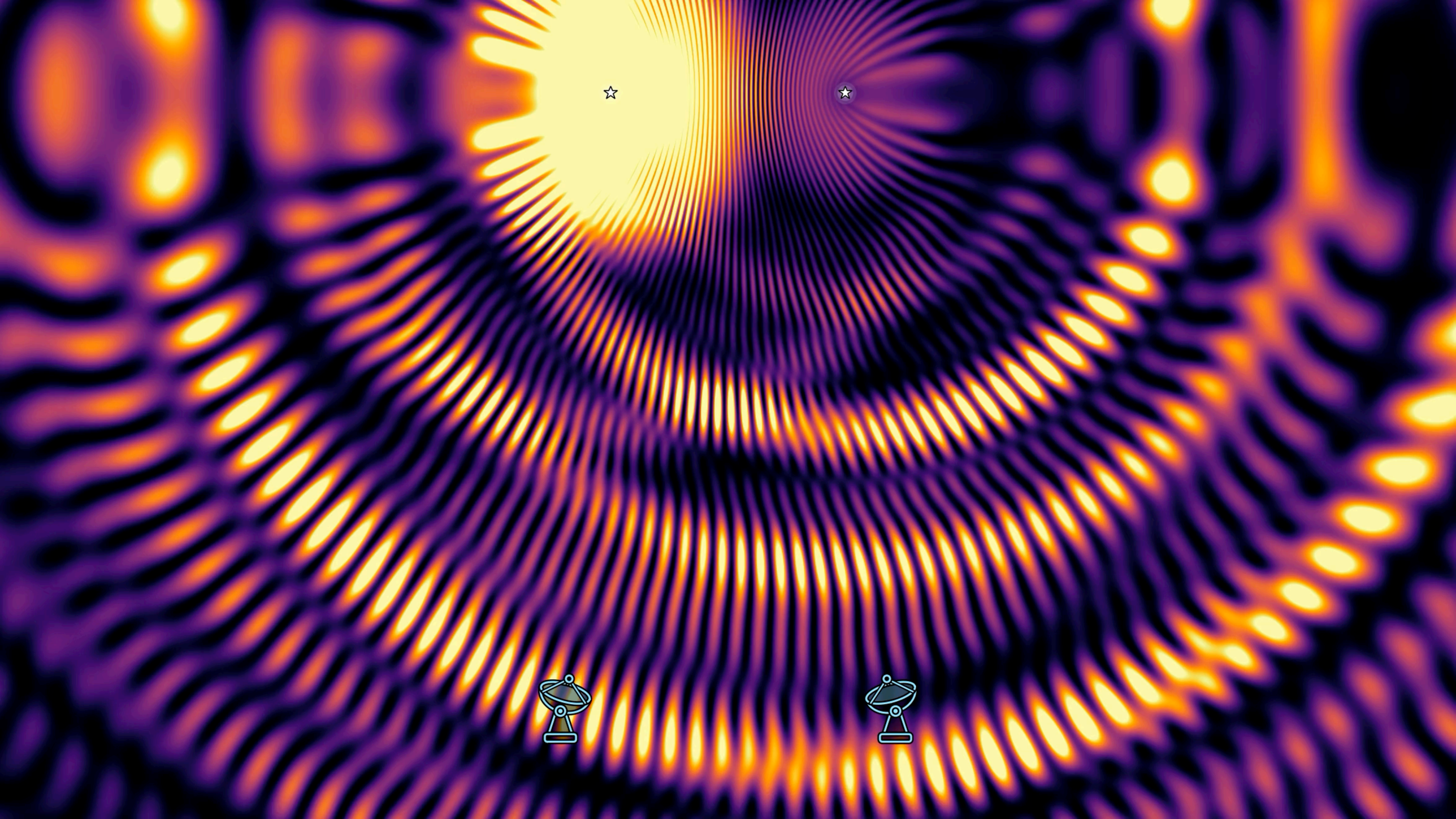


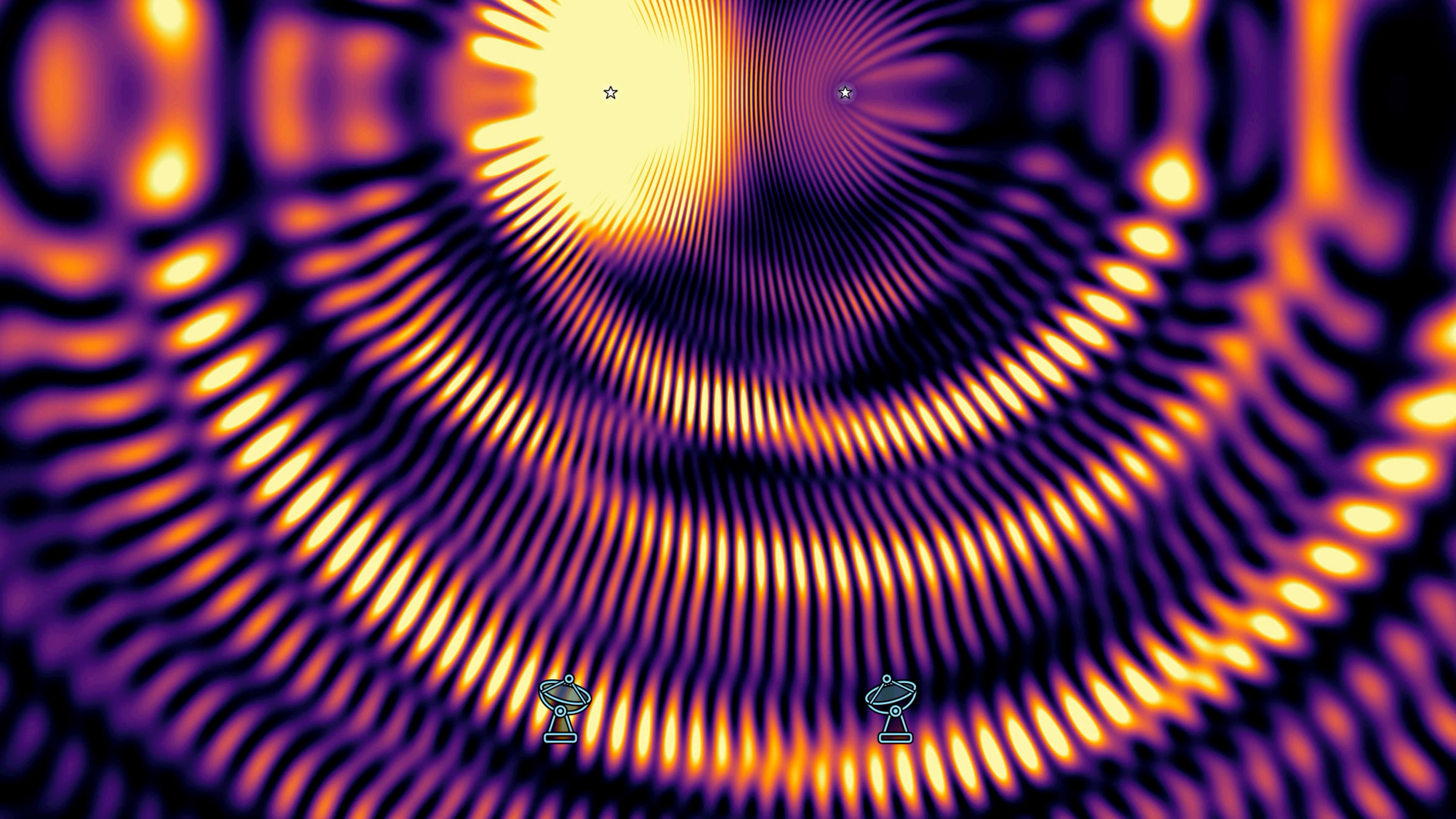












Intensity Correlations

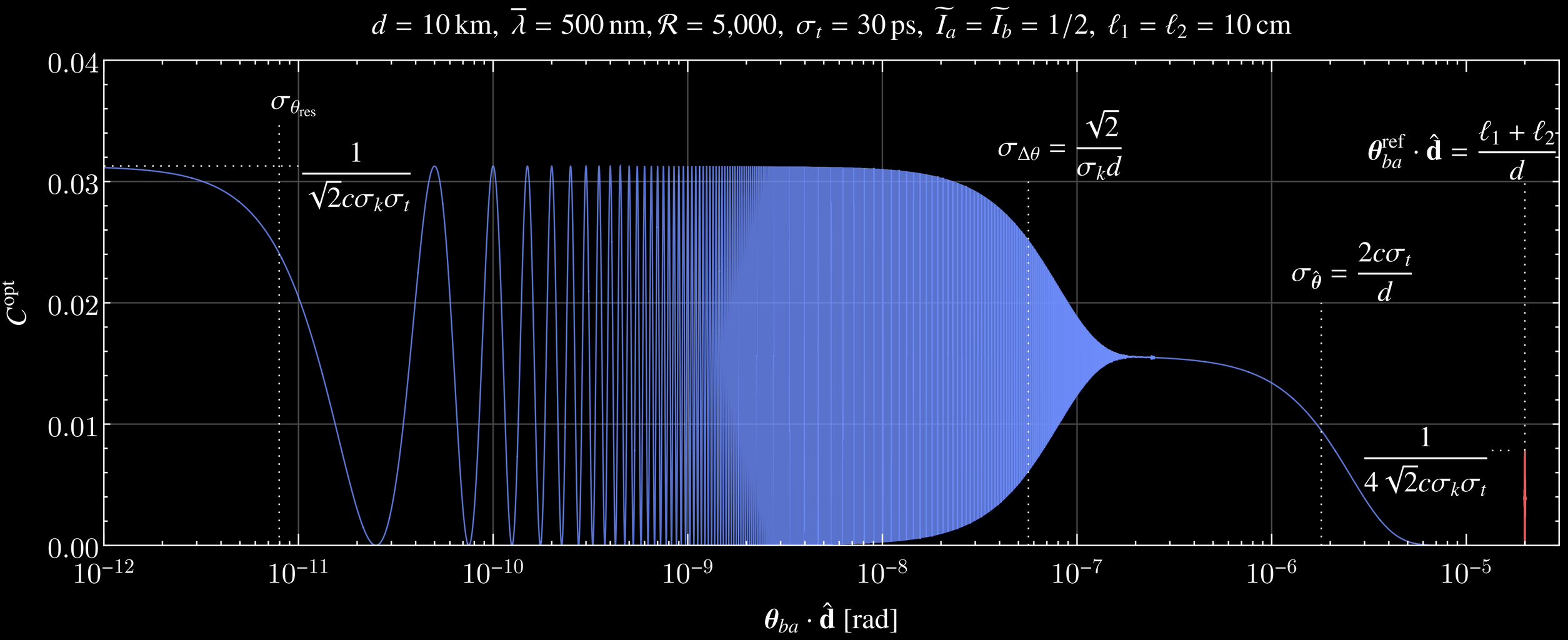
$$C = \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle} - 1$$

$$= |\text{image FT at angular wavenumber } k\boldsymbol{d}|^2$$

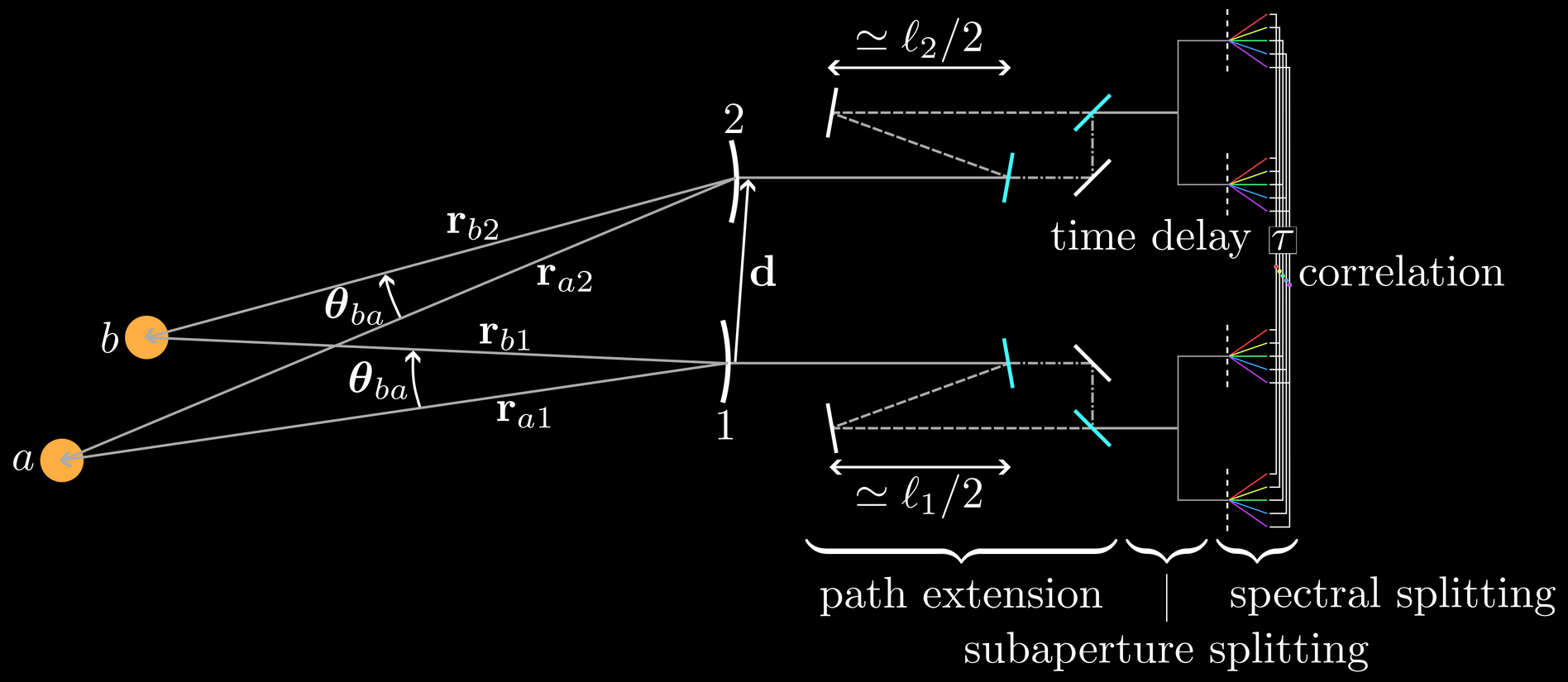
Intensity Correlations

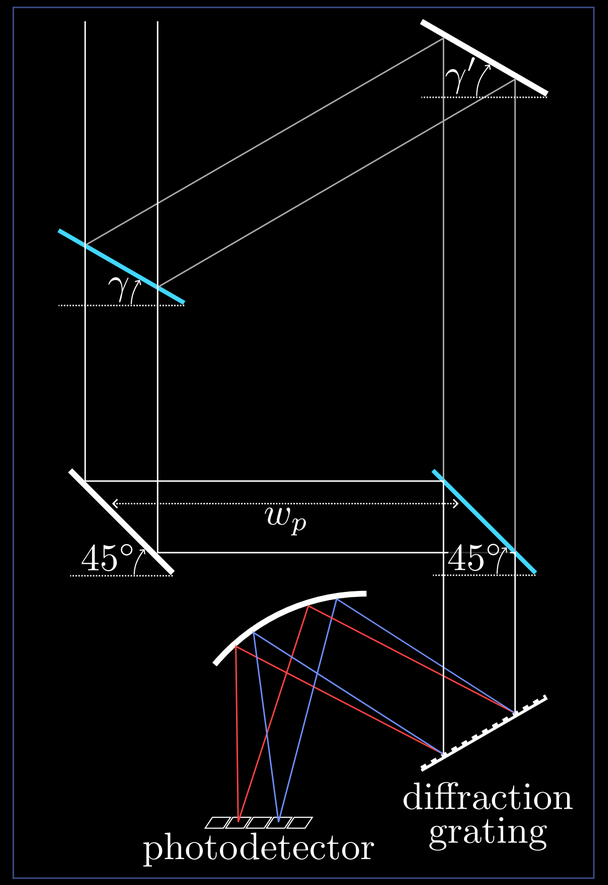
$$C = \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle} - 1$$

$$= |\text{image FT at angular wavenumber } k\boldsymbol{d}|^2$$



Extended-Path Intensity Correlation (EPIC)



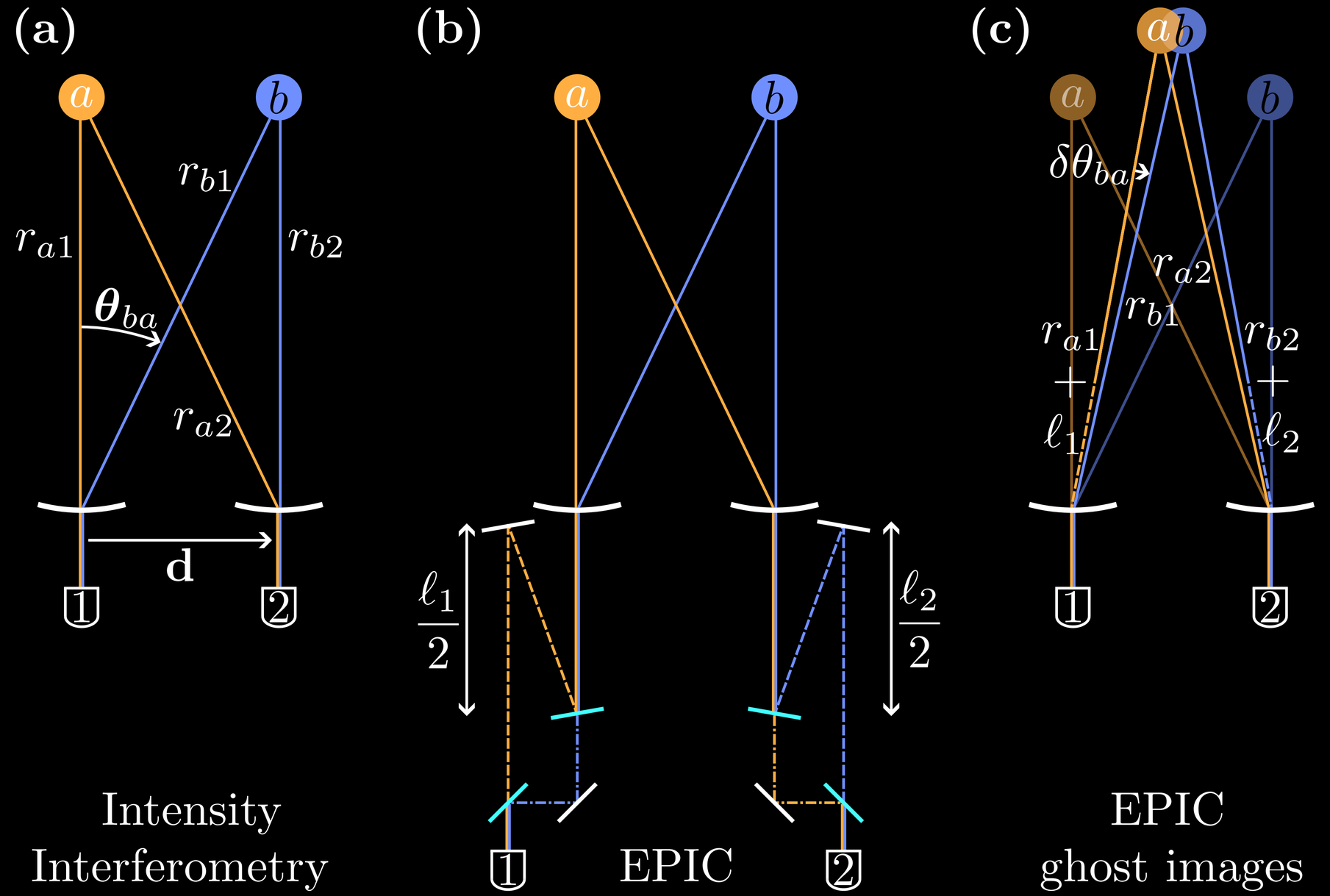


✅ differential astrometry over “large” field of view

[KVT, M. Baryakhtar, M. Galanis, N. Weiner; arXiv:2307.03221]

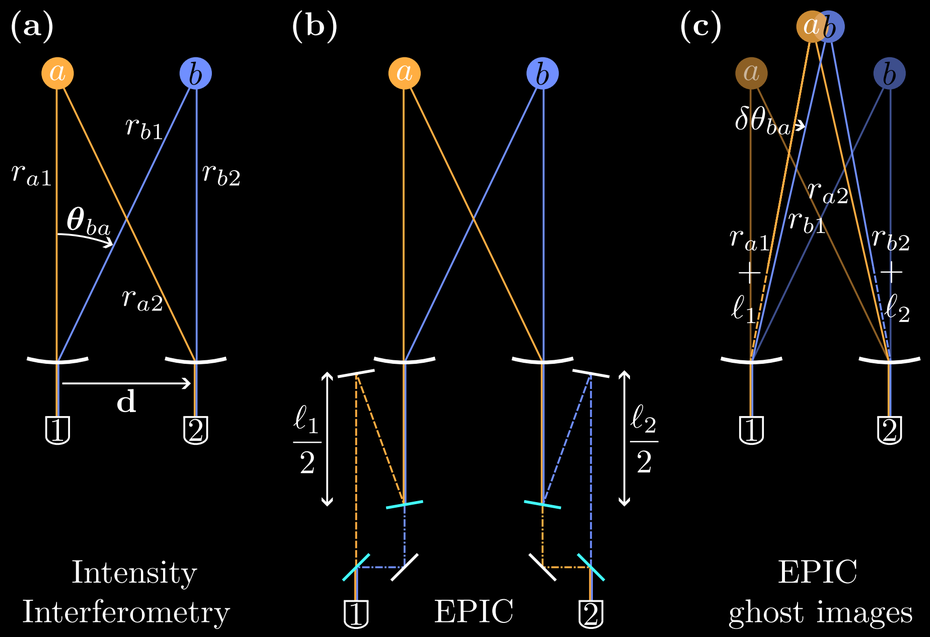
[M. Galanis, KVT, M. Baryakhtar, N. Weiner; arXiv:2307.06989]

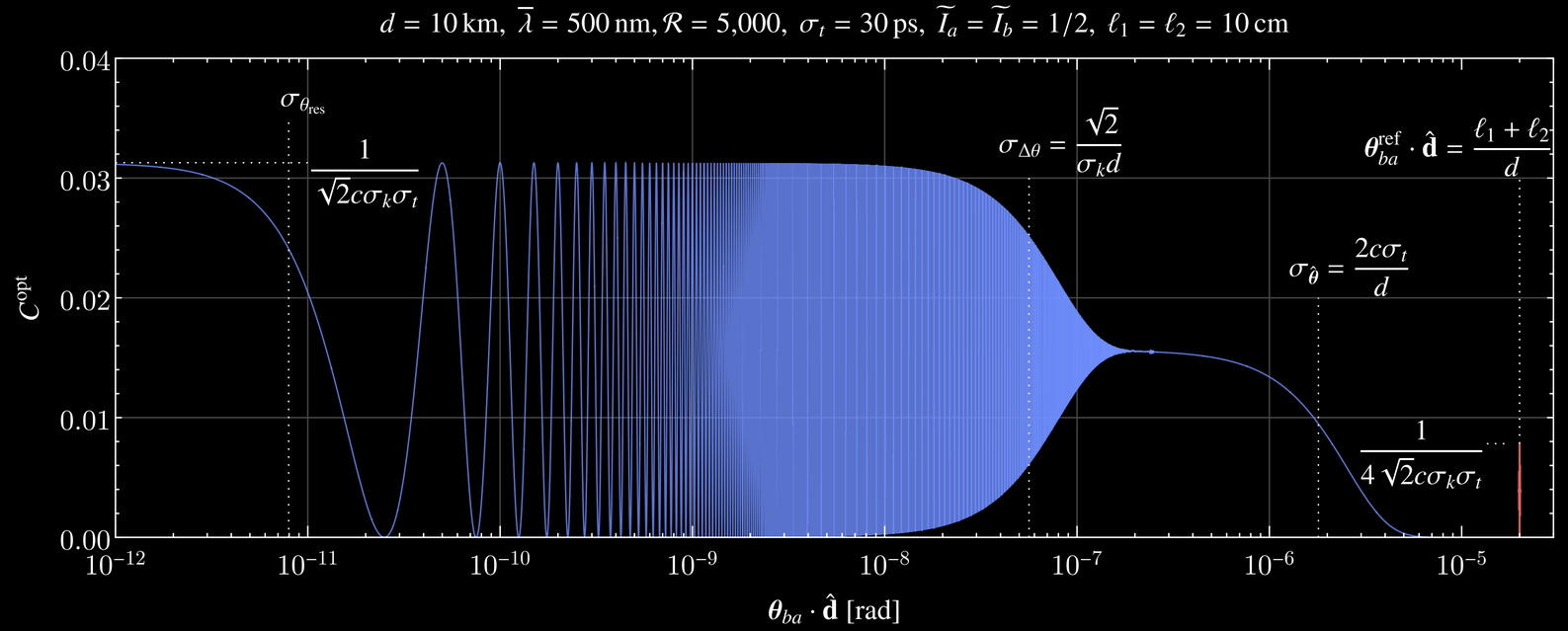
EPIC: Basic Principle

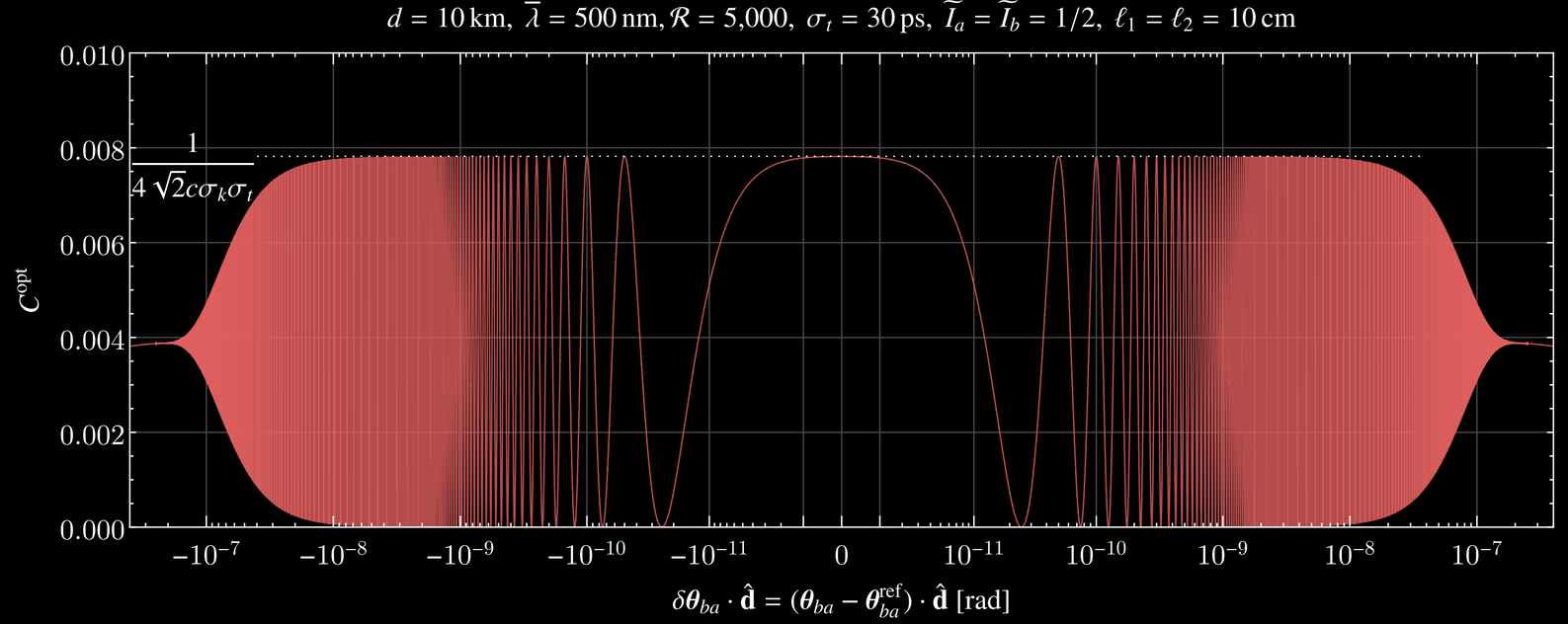


EPIC

$$C = \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle} - 1$$
$$= |\text{image FT at angular wavenumber } \boldsymbol{kd}|^2$$







Future Phases of EPIC

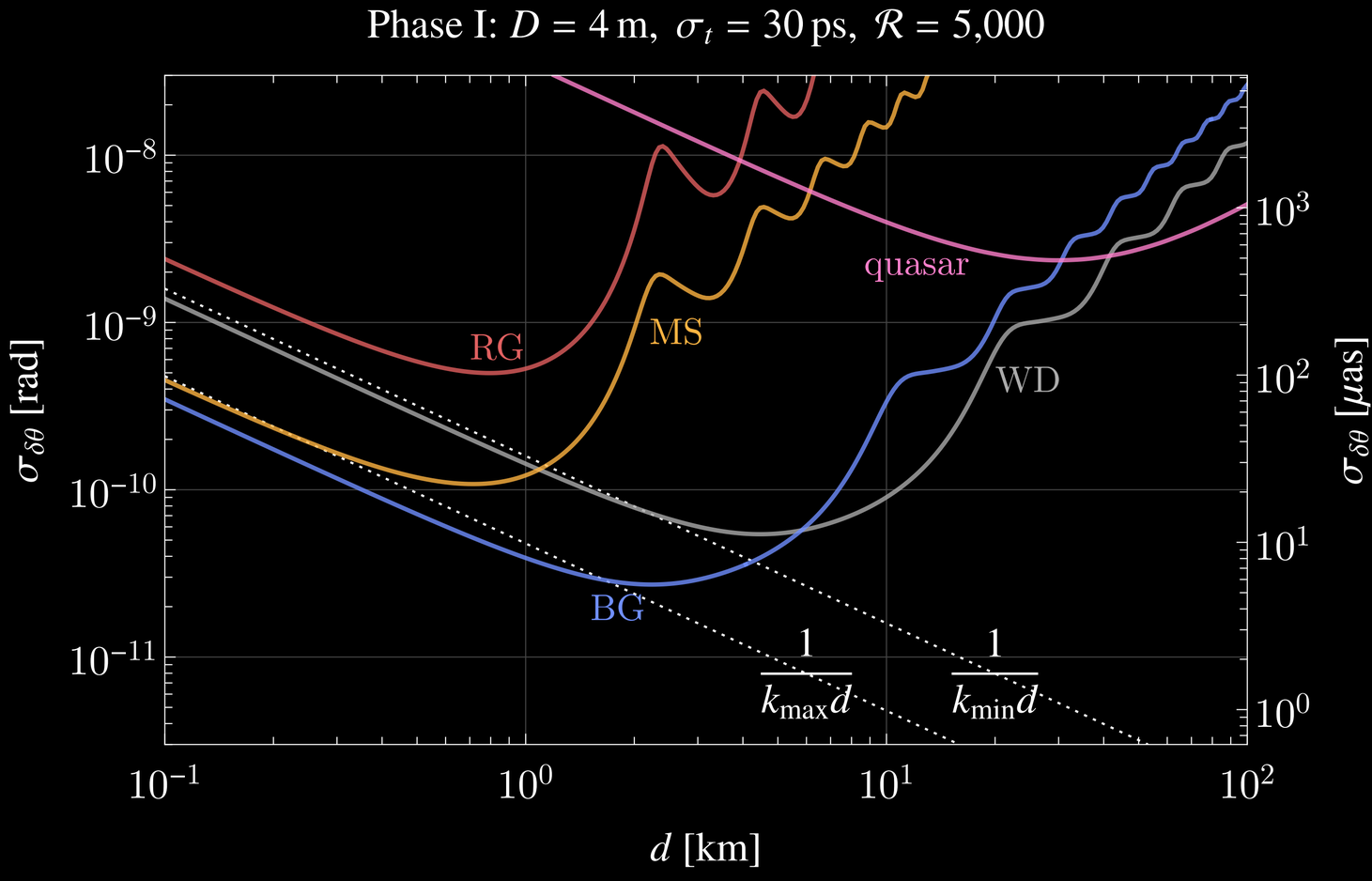
Astrometric Performance on two Sun-like stars at 100 pc

	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

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

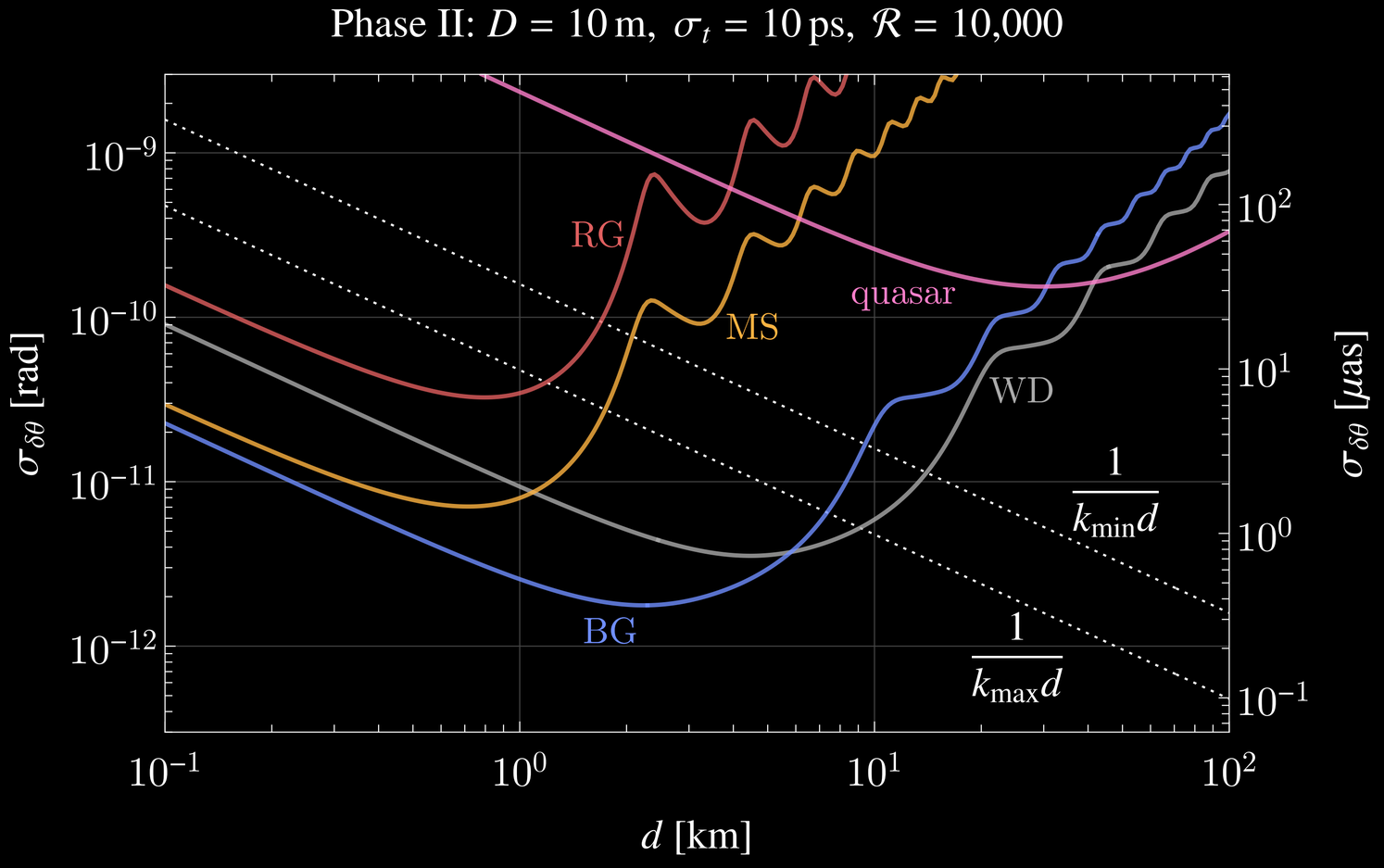
$$\sigma_{\delta\theta} \sim \frac{1}{\sqrt{N_1 N_2}}\,\frac{1}{Ad}\sqrt{\frac{\sigma_t}{t_{\rm shot}}}\sqrt{\frac{\sigma_k}{k}}\,\frac{1}{T_s^3\theta_s^2}$$



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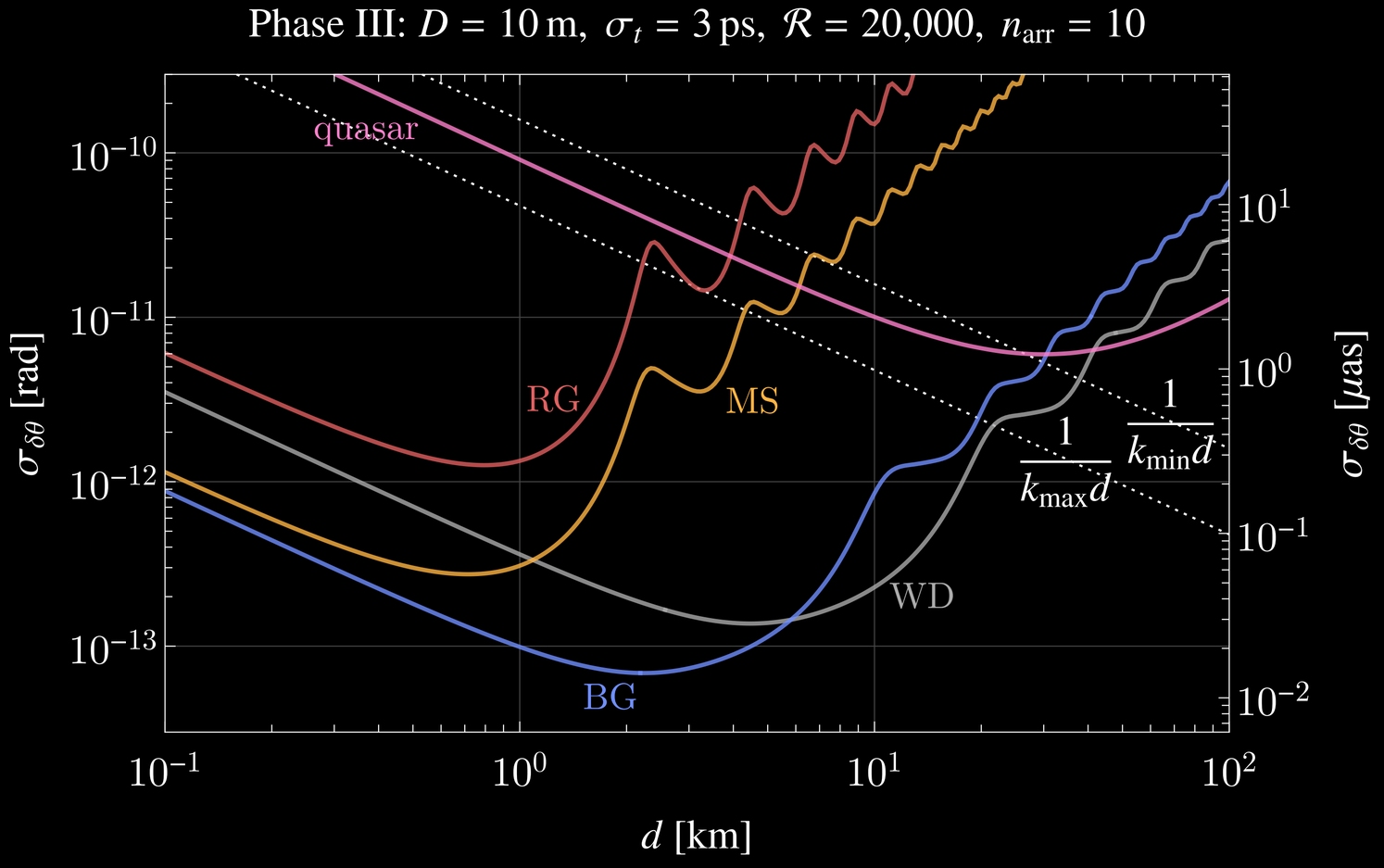
$$\sigma_{\delta\theta} \sim \frac{1}{\sqrt{N_1 N_2}}\,\frac{1}{Ad}\sqrt{\frac{\sigma_t}{t_{\rm shot}}}\sqrt{\frac{\sigma_k}{k}}\,\frac{1}{T_s^3\theta_s^2}$$



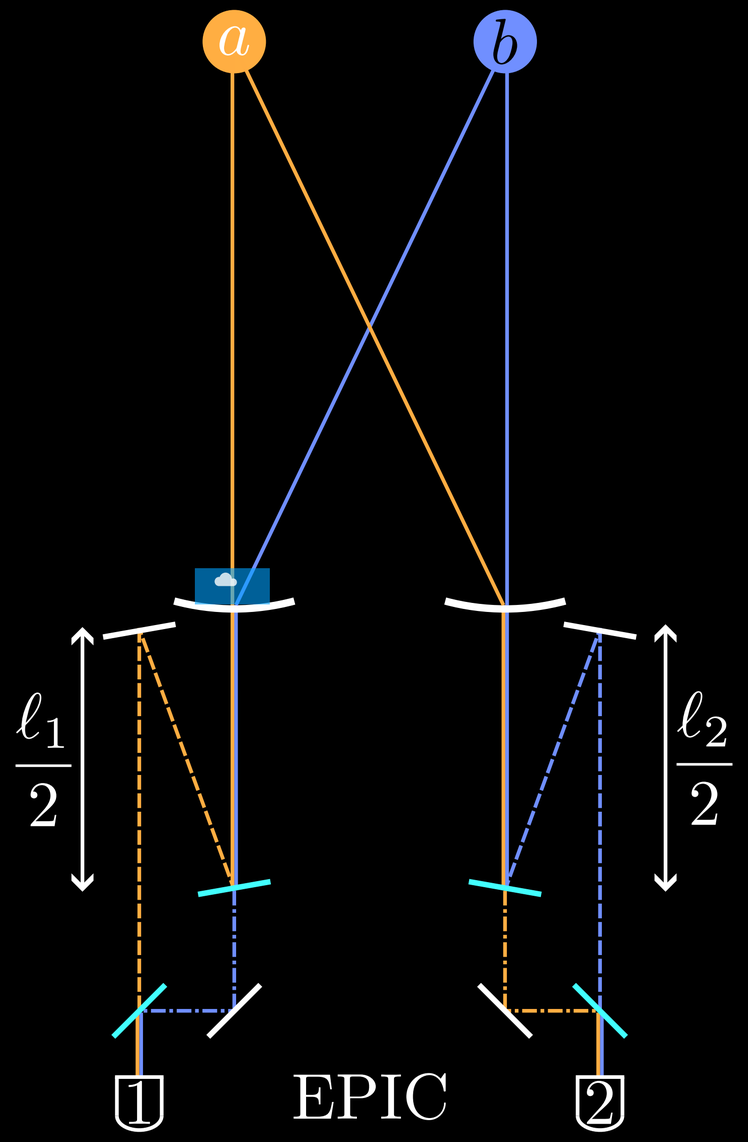
Light-Centroiding Precision

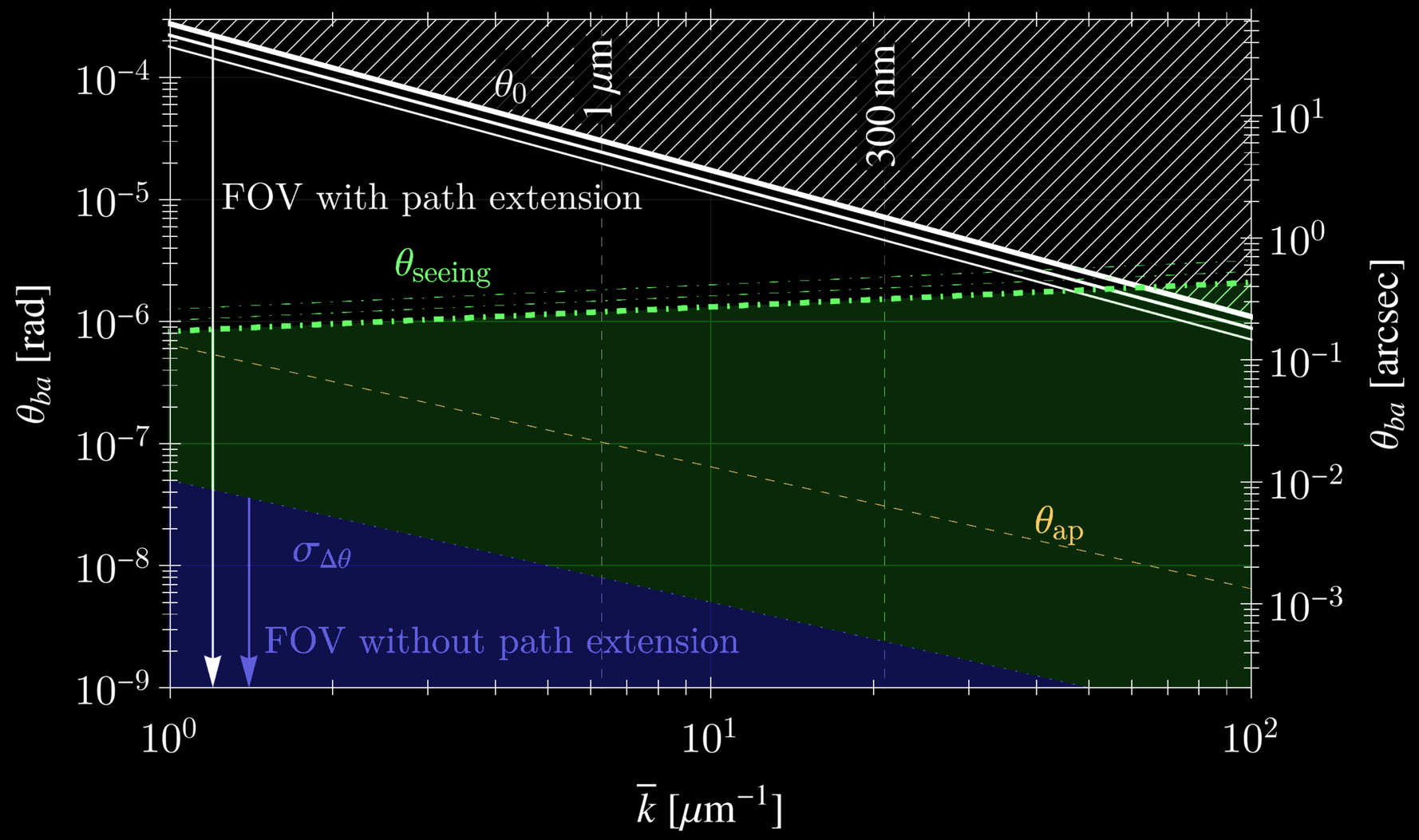
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$$\sigma_{\delta\theta} \sim \frac{1}{\sqrt{N_1 N_2}}\,\frac{1}{Ad}\sqrt{\frac{\sigma_t}{t_{\rm shot}}}\sqrt{\frac{\sigma_k}{k}}\,\frac{1}{T_s^3\theta_s^2}$$

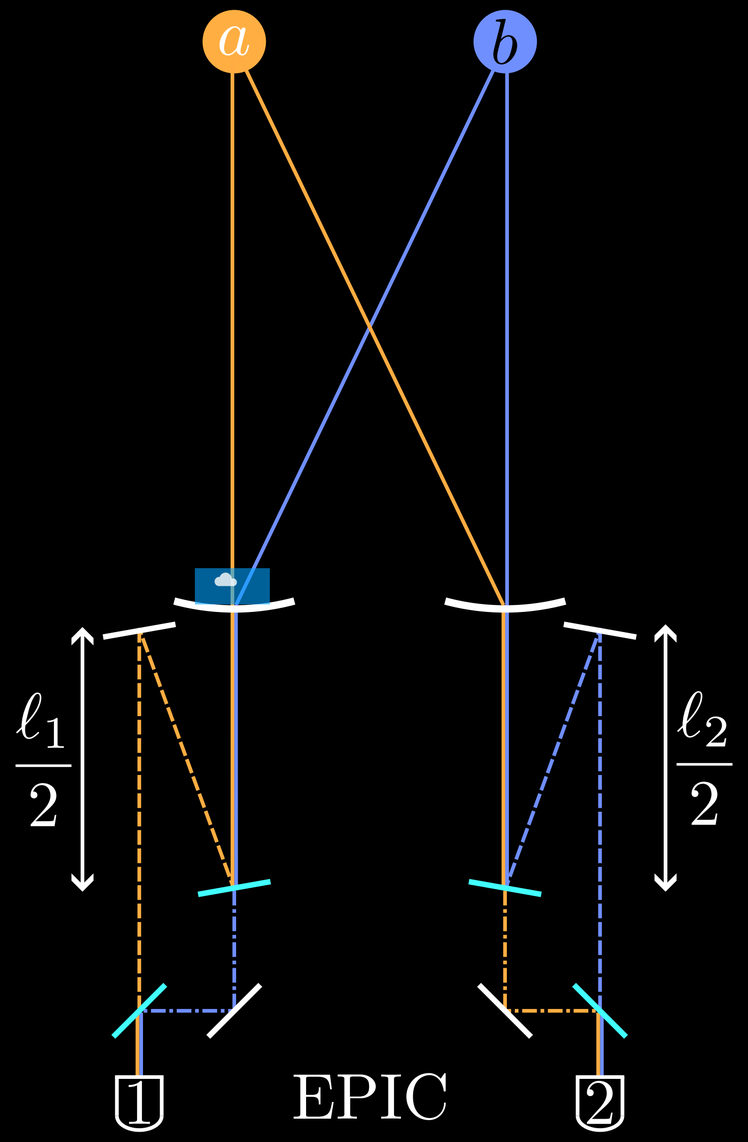


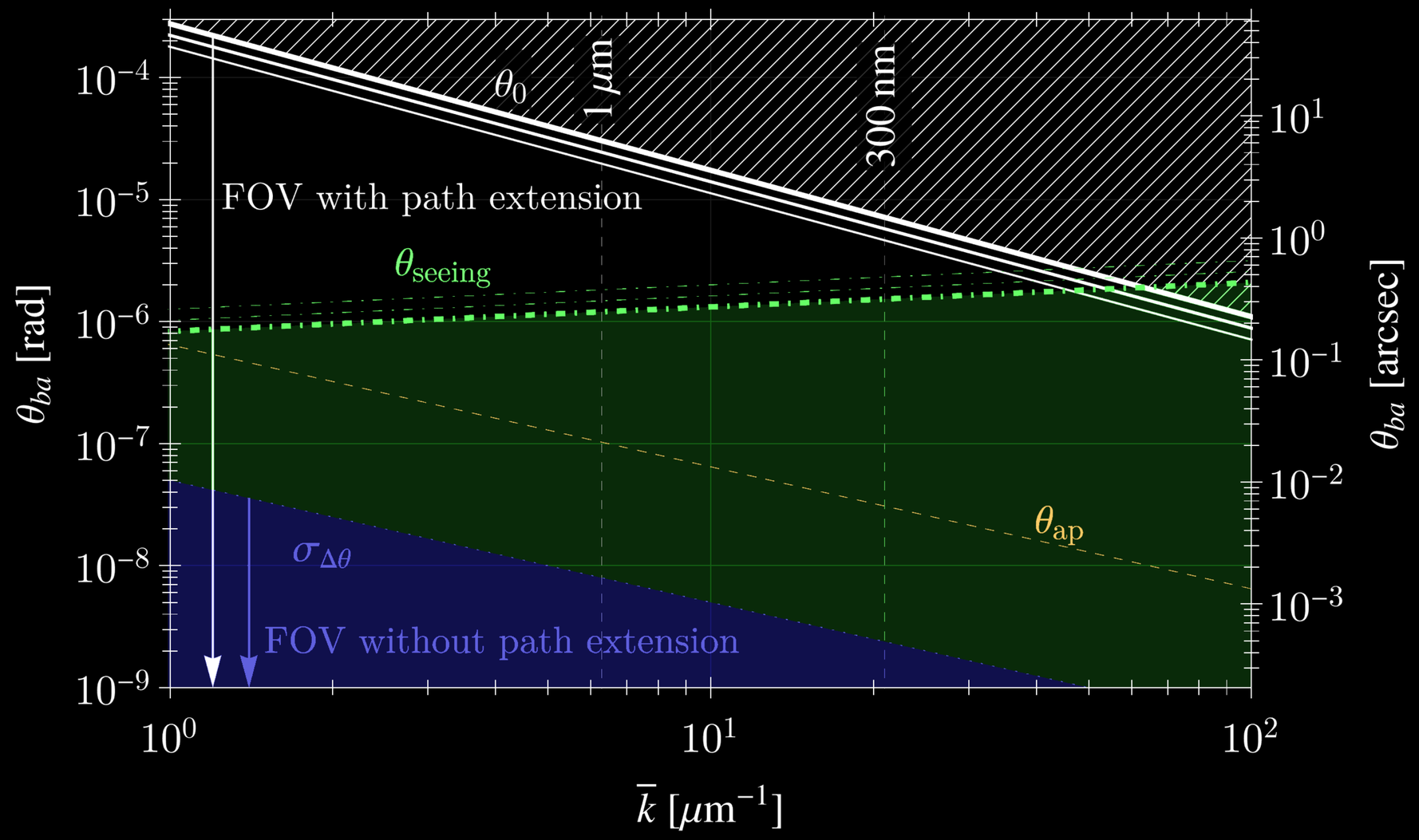
Atmospheric Aberrations



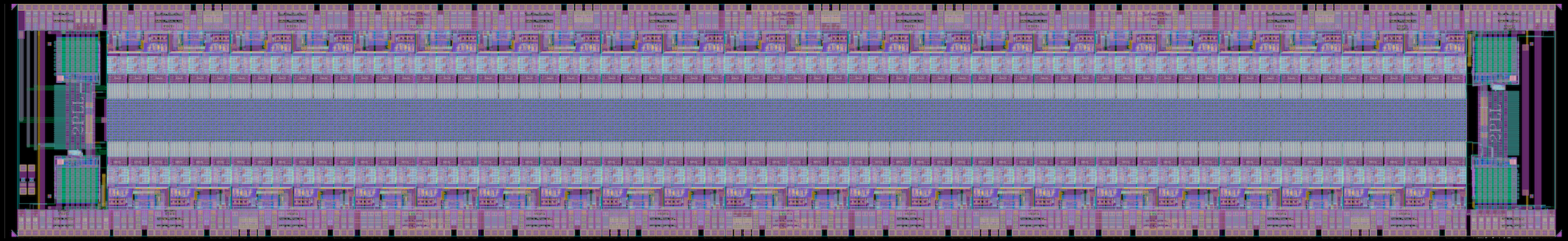


Atmospheric Aberrations





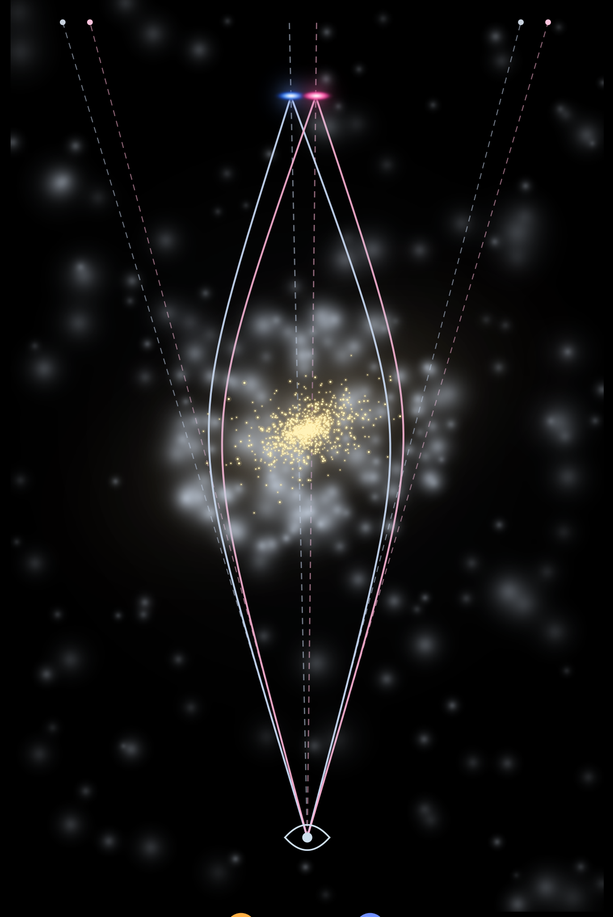
QUASAR Project

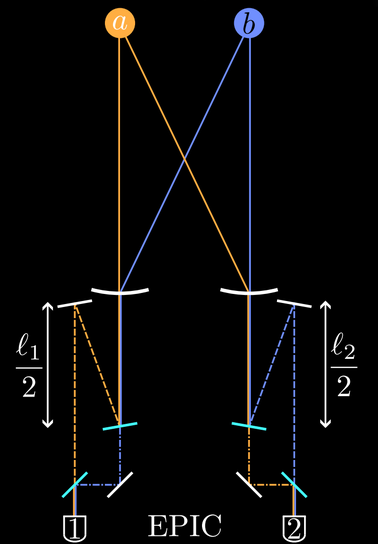


528×16-pixel SPAD, $\sigma_t = 5\,\mathrm{ps}$

[Roland Walter]

Conclusions





dark matter substructure at sub-stellar masses

uncovered by

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

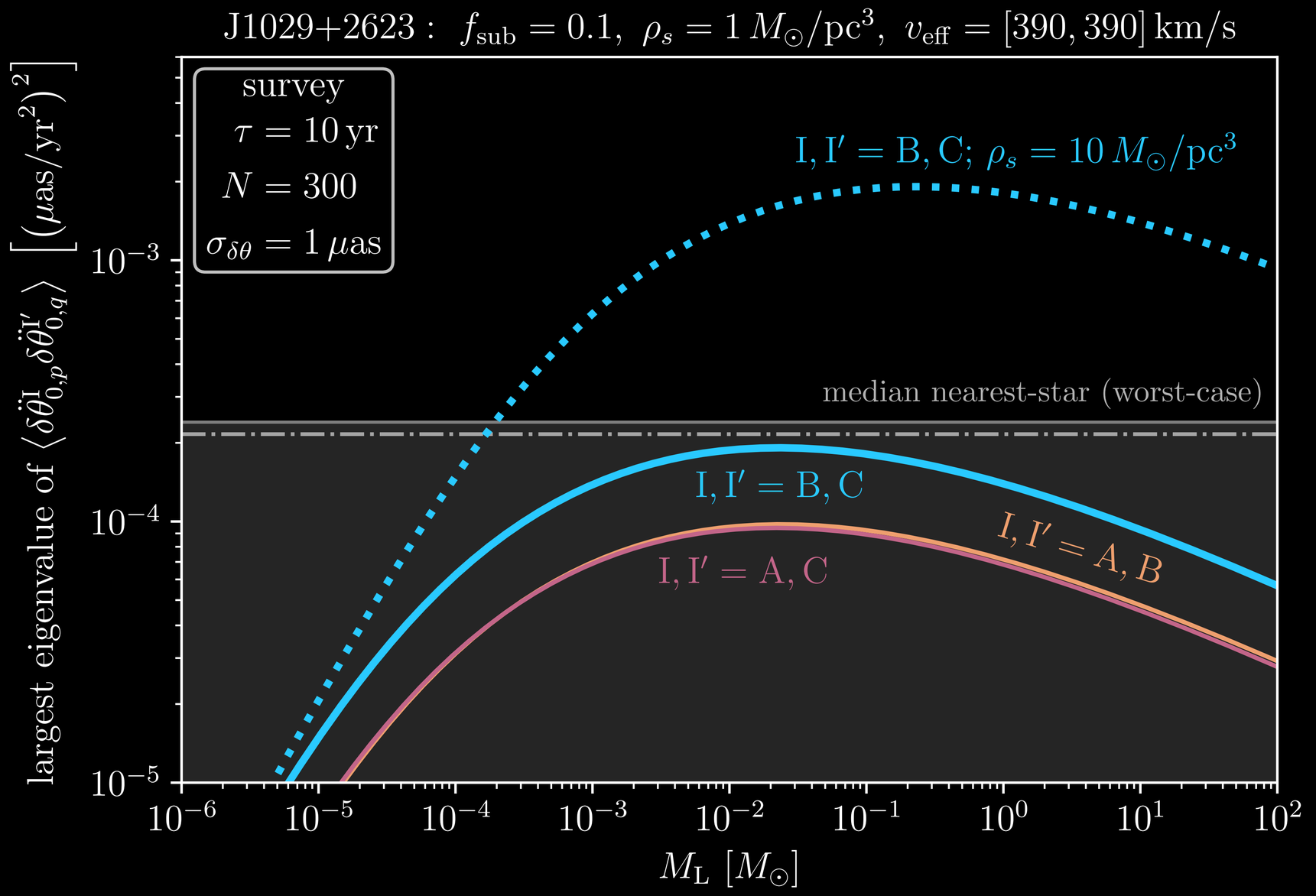
on multiply imaged quasar images separated by less than a few arcseconds

"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

Back-up Slides

Lensing-induced Acceleration



Lensing-induced Stochastic Noise

