UNIVERSITÄT BIELEFELD

Faculty of Physics

SEARCHING FOR ULTRALIGHT ALPS

with polarimetric observations of gravitational lenses

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In collaboration with Aritra Basu & Dominik Schwarz

Les Houches Summer School

'Dark Universe'

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Introduction and Motivation

QCD Axions are motivated by the strong CP problem

- *A solution was proposed by Peccei and Quinn in 1977*
- *This solution calls for the existence of a Nambu-Goldstone boson which was named 'Axion'*

Axion-like particles (ALPs) are general class of pseudo scalars which generically appear in well-motivated high energy theories and string theory

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} \partial_\mu a \, \partial^\mu a + \frac{1}{4} g_{a\gamma} \, a \, F_{\mu\nu} \tilde{F}^{\mu\nu} - \phi(a)$$

Kinetic term (Maxwell's equation) — Scalar field — Scalar-photon field coupling — ALP potential

ALPs are a candidate of Cold Dark Matter

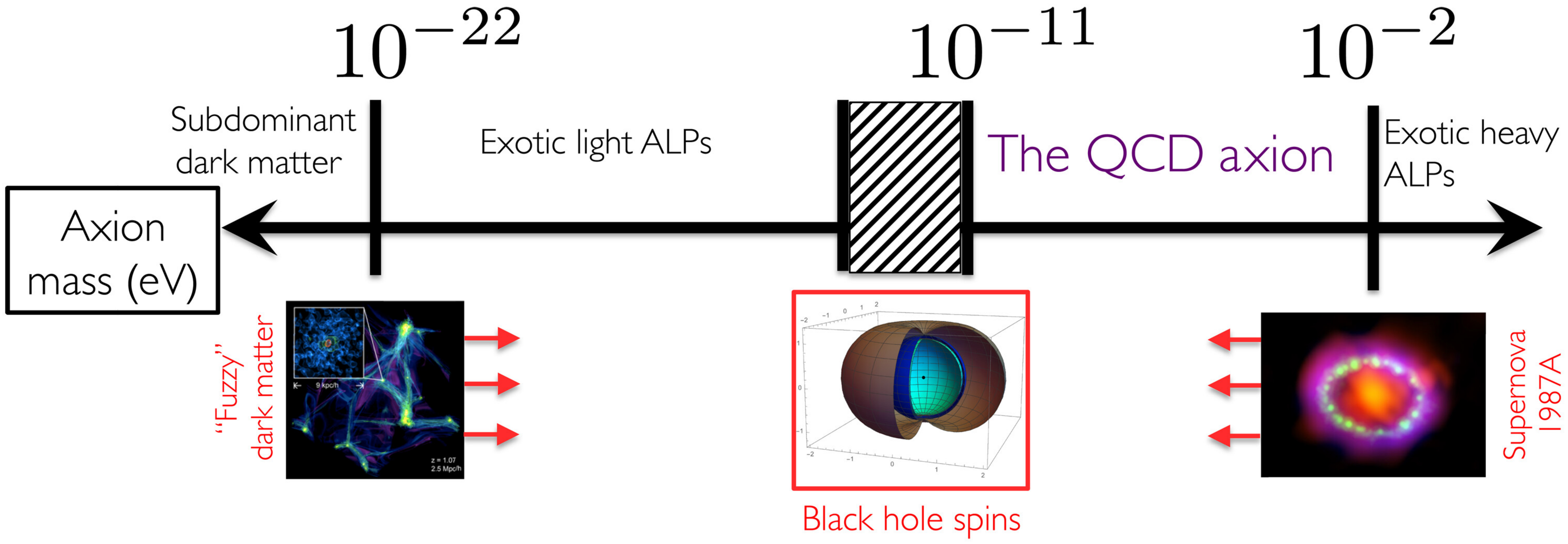


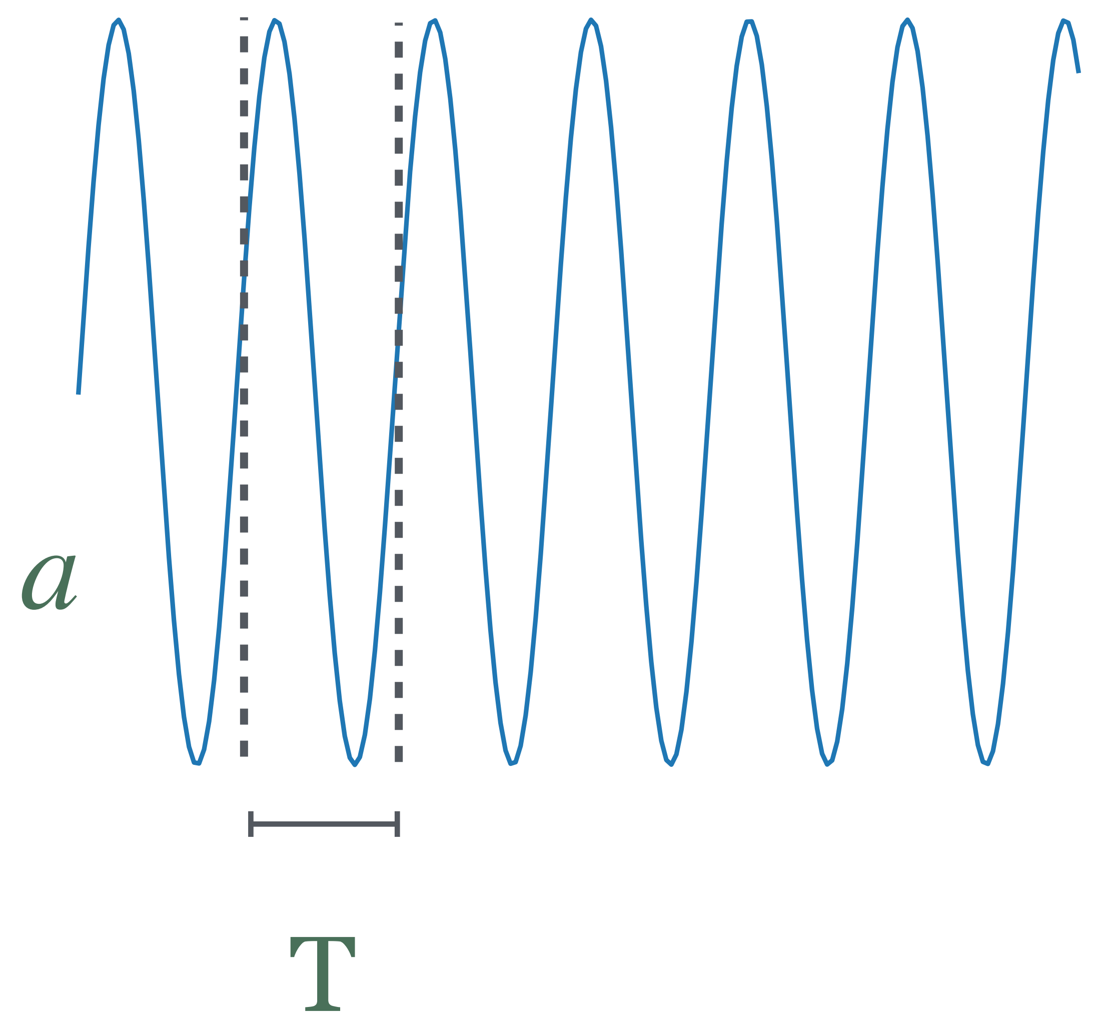
Image: Chadha-Day et al 2022, Science Advances

Klein-Gordon equation of motion:

$$\ddot{a} + 3H\dot{a} + m^2 a = 0$$

Axion-like Particles (ALPs)

Solving the Klein-Gordon equation of motion within gravitationally bound structure of Dark Matter halo



ALP field oscillates

$$a(t, x^i) = \frac{\sqrt{2\rho_a(x^i)}}{m_a} \sin\left[m_a t + \delta(x^i)\right]$$

with a time period

$$T = \frac{2\pi}{m_a} \approx 4 \times 10^7 \text{s} \left(\frac{10^{-22}\ \text{eV}}{m_a}\right)$$

& de Broglie wavelength

$$\frac{\lambda_{dB}}{2\pi} = \frac{\hbar}{m_a v} \approx 60\ \text{pc} \left(\frac{10^{-22}\ \text{eV}}{m_a}\right) \left(\frac{10^{-3} c}{v}\right)$$

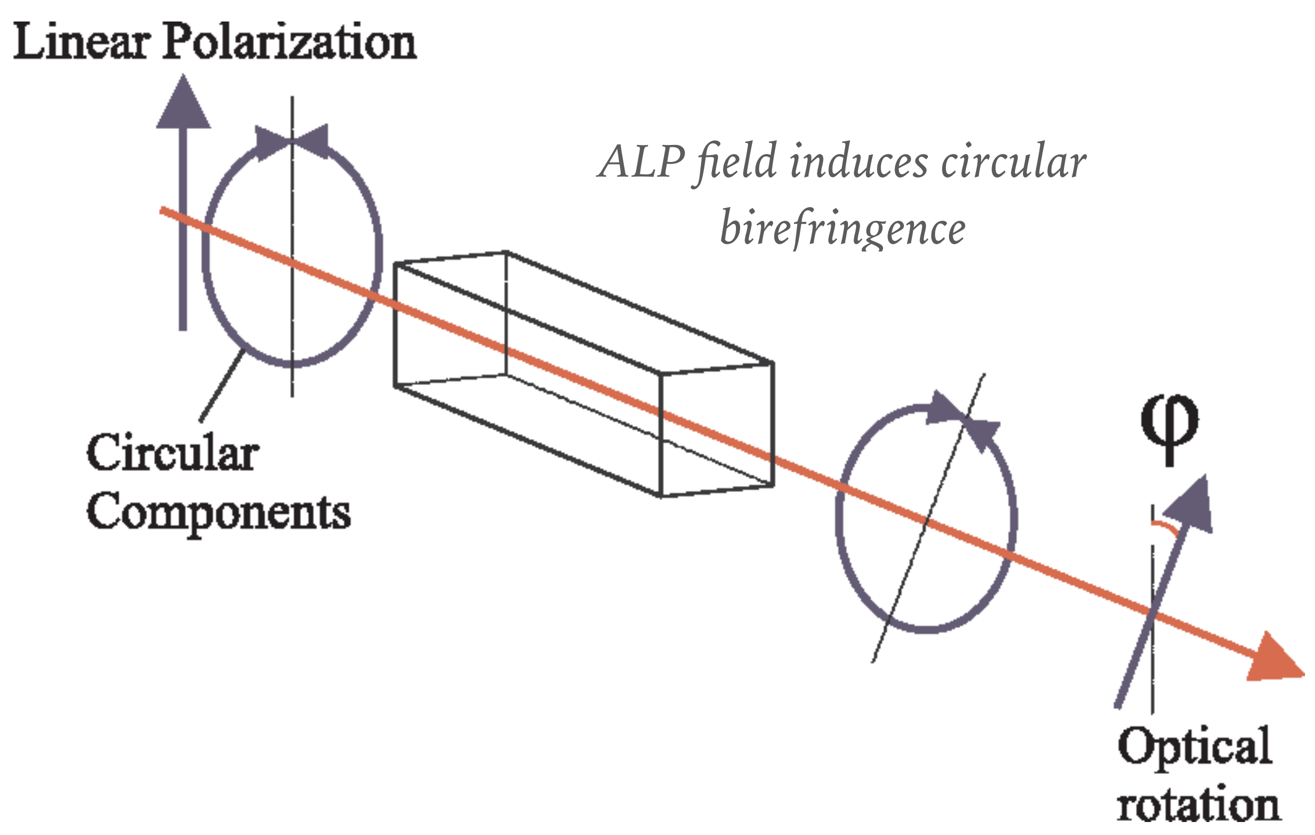
ALP search technique

- *ALP-photon interaction gives rise to birefringence*

D. Harari & P. Sikivie 1992, S. M. Carroll 1998

- *Achromatic rotation in ALP field*

D. J. Schwarz et al. 2021, D. Blas et al 2020, M. A. Fedderke et al 2019, J. I. McDonald & L. B. Ventura 2019



- *ALP field oscillates in time as* $T = \frac{2\pi}{m_a}$

$\Longrightarrow$ *Polarisation angle also oscillates*

Amount of rotation depends on the ***coupling constant*** $g_{a\gamma}$

Gives a measure of ***ALP mass*** m_a

Basu et al. 2021, Phys. Rev. Lett.

ALP induced birefringence signature

- Polarization angle observed

$$\theta_{\rm obs} = \theta_{\rm src} + \delta\theta_{\rm ALP} + \delta\theta_{\rm cal}$$

Basu et al. 2021, Phys. Rev. Lett.

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calibration error $(\sim 2 - 3$ *degs*$)$

$$\theta_{\rm src} \equiv \theta_{\rm src}(t, \nu, {\rm RM}, \theta_0)$$

$\theta_0 \equiv$ *intrinsic source polarization (unknown)*

RM $\equiv$ *Rotation Measure*

Basu et al. 2021, Phys. Rev. Lett.

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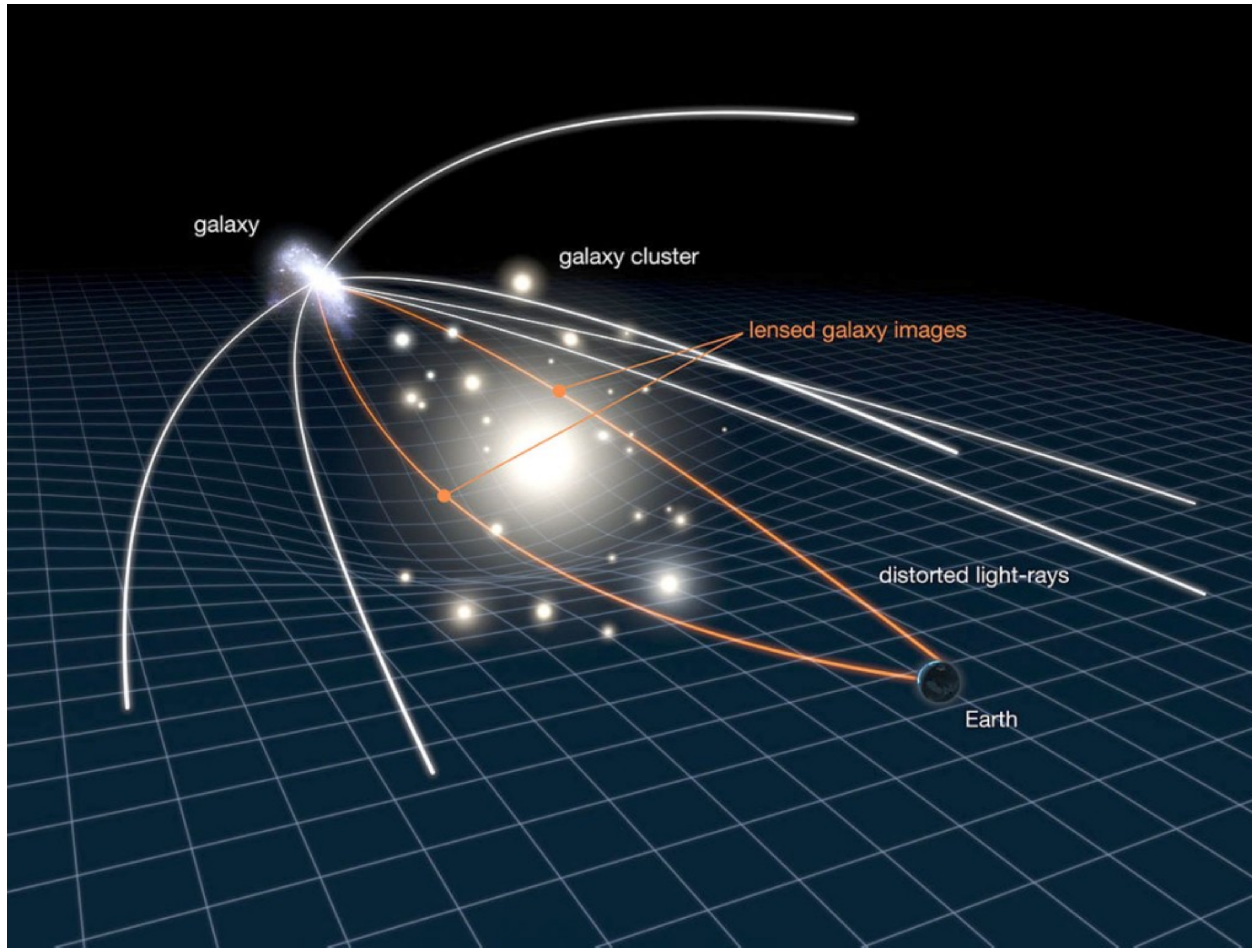


Image: NASA/ESA

- Gravitational lensing to the rescue

$$\Delta\theta_{\rm AB} = \theta_{\rm A} - \theta_{\rm B}$$

- Differential birefringence angle (from theory)

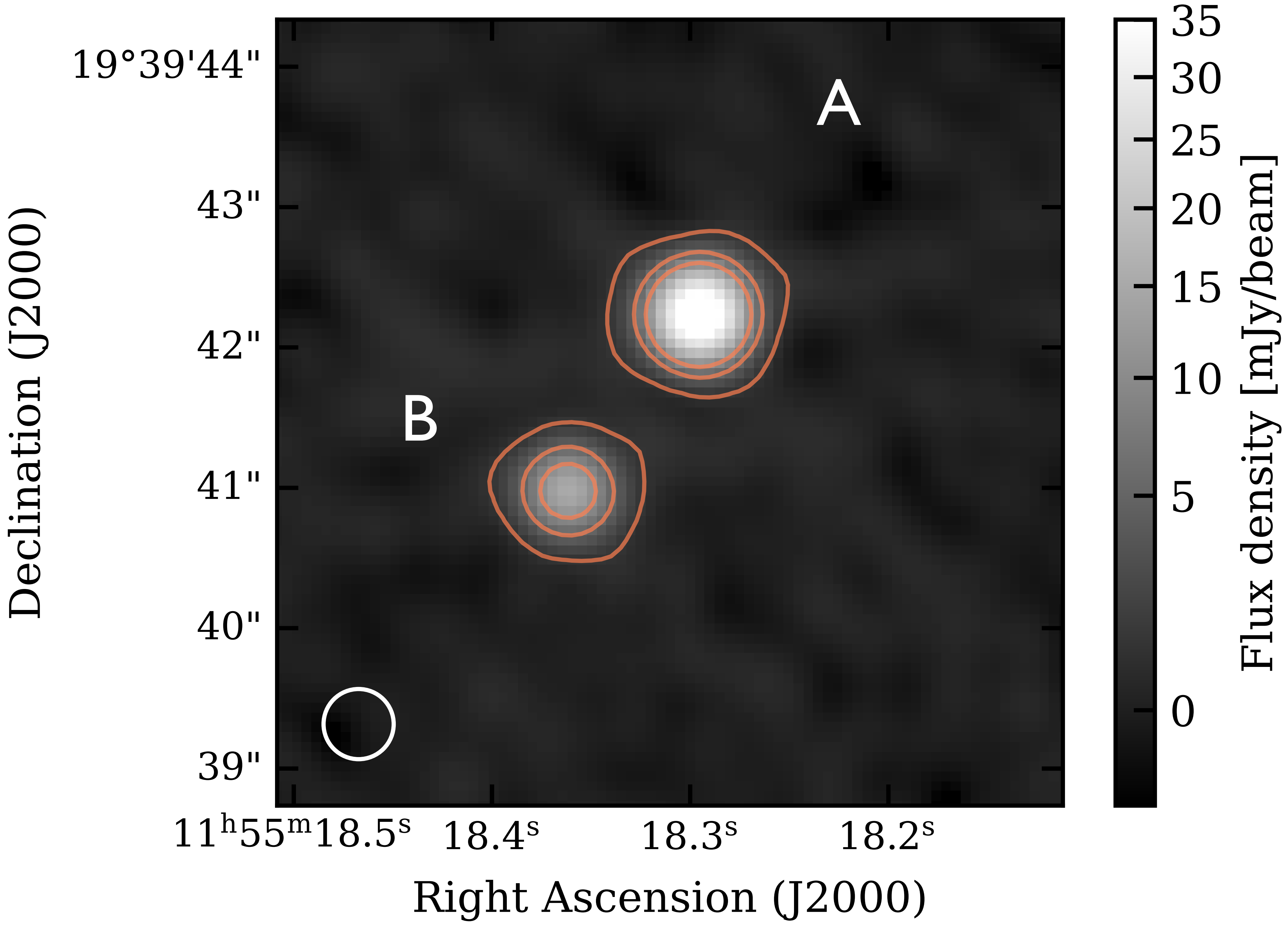
$$\Delta\theta_{\rm AB} = K \sin\left[\frac{m_a \Delta t}{2}\right] \sin\left[m_a t_{\rm em} + \delta_{\rm em} - \frac{\pi}{2}\right]$$

$$K = 10^\circ \left[\frac{\rho_{a,\,\rm em}}{20\ {\rm GeV\ cm^{-3}}}\right]^{1/2} \left[\frac{g_{a\gamma}}{10^{-12}\ {\rm GeV^{-1}}}\right] \left[\frac{m_a}{10^{-22}\ {\rm eV}}\right]^{-1}$$

Basu et al. 2021, Phys. Rev. Lett.

Observations

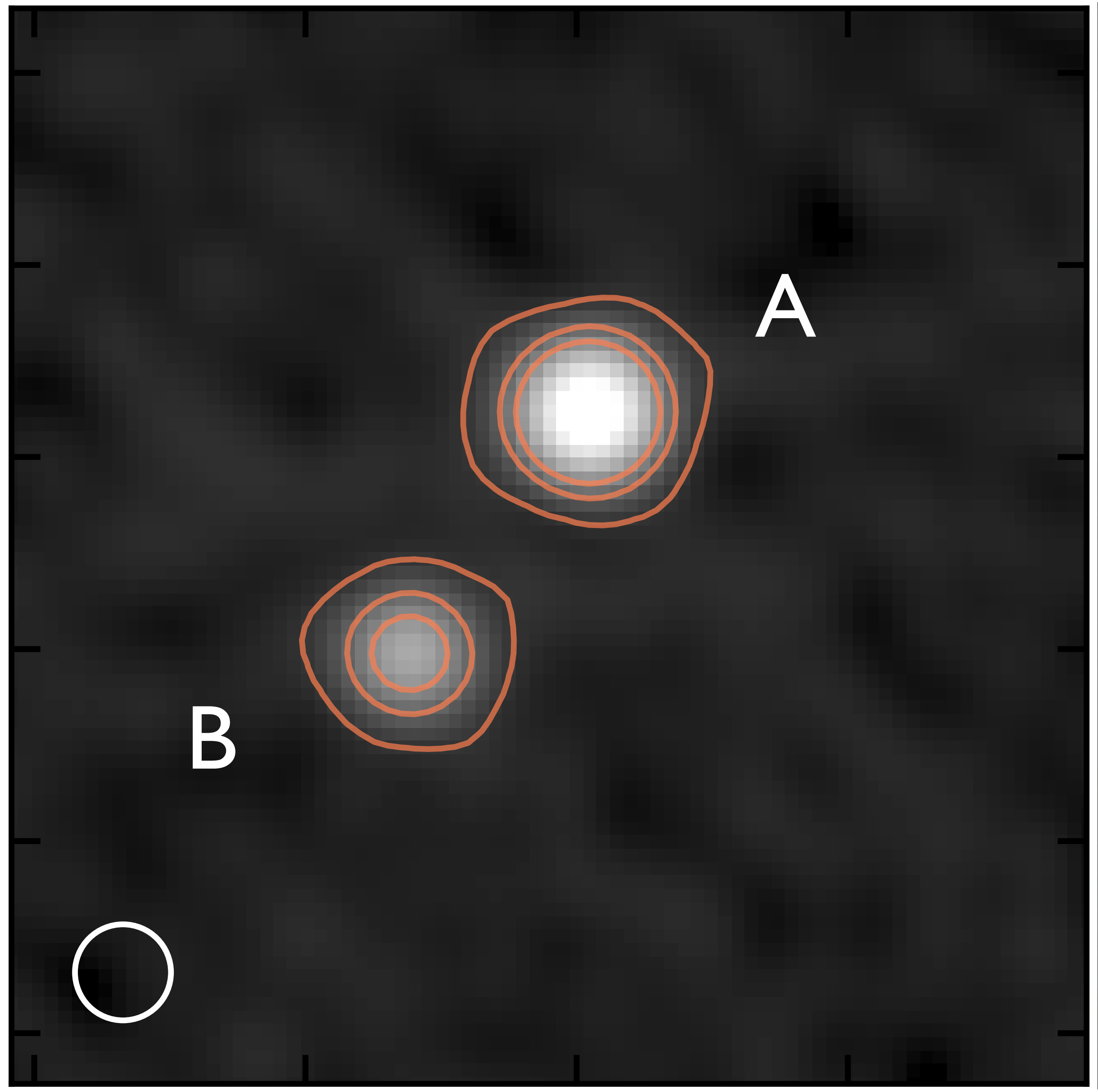
Total intensity image at 3 GHz



B1152+199

- VLA A-configuration
  - — Resolution of 0.5 x 0.5 arcsec
- 1-8 GHz frequency range
  - — Broadband spectro-polarimetric data
- 5 epochs in spring 2022
  - — 20 days cadence over a duration of 3 months
- All Stokes parameters

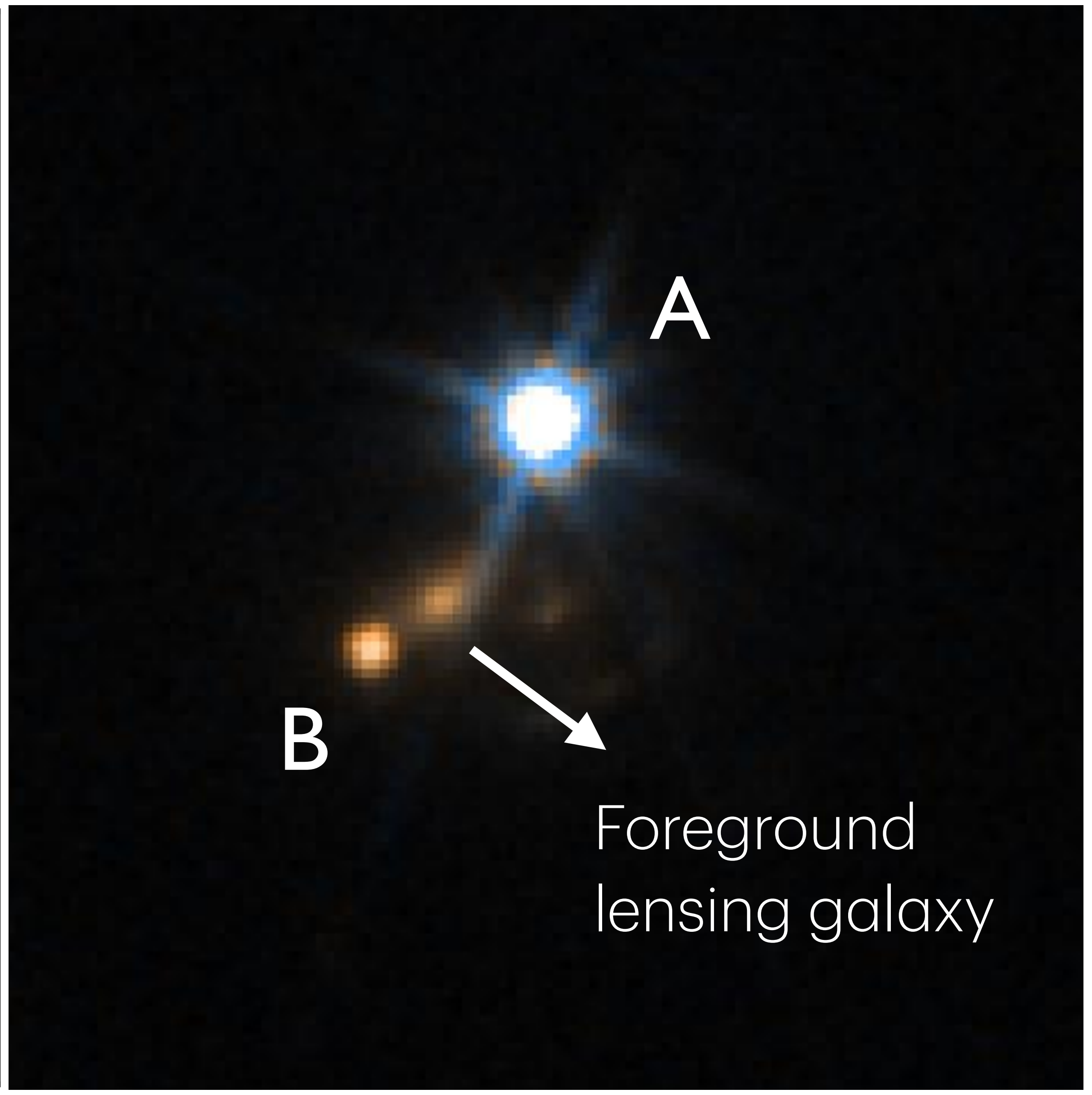
Radio vs Optical image



VLA image

Resolution : 0.5 x0.5 arcsec

Image separation: 1.56 arcsec



HST image

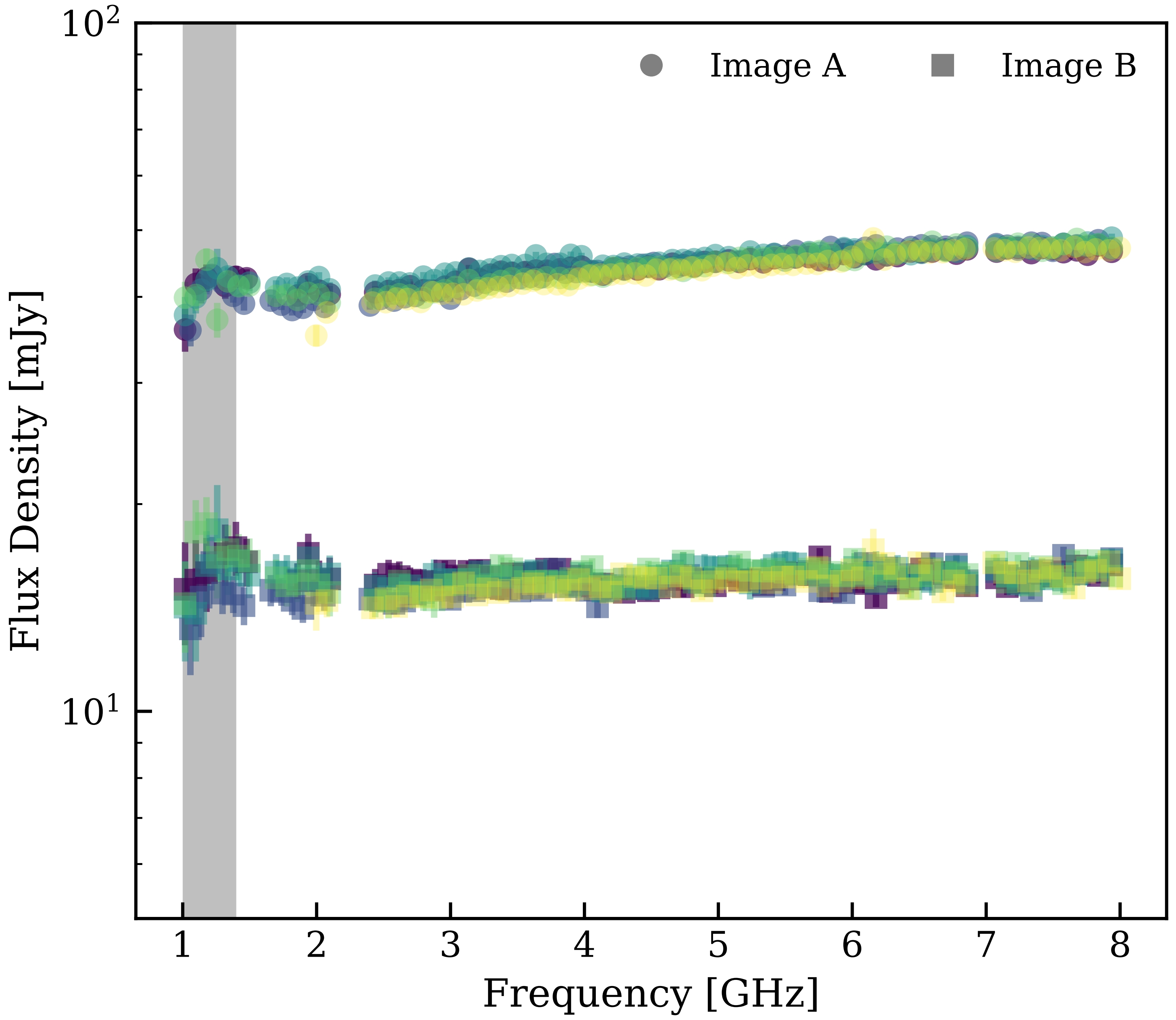
Resolution ~ 0.1 x0.1 arcsec

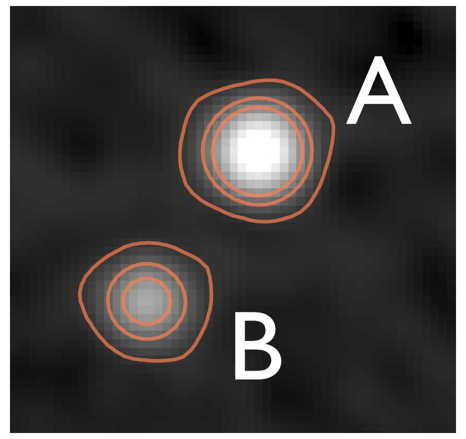
Redshifts

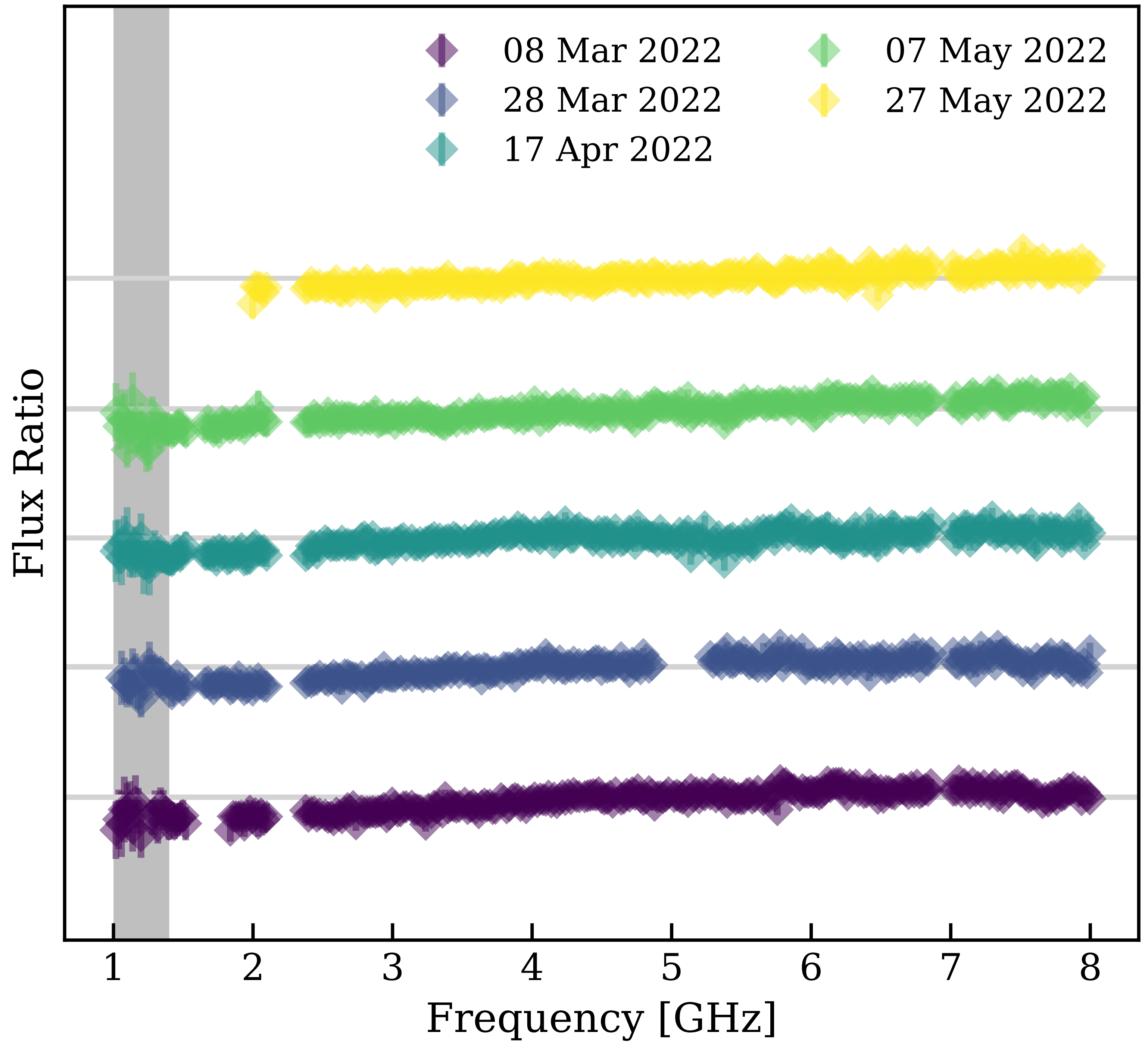
$z_{\mathrm{lens}} = 0.439$

$z_{\mathrm{qso}} = 1.019$

Continuum Spectrum







- Magnification ratio

$$\mu = \frac{S_A}{S_B} \sim 3:1$$

- **No intrinsic variability**

$$\theta_{\mathrm{src}} \equiv \theta_{\mathrm{src}}(\cancel{t}, \nu, \mathrm{RM}, \theta_0)$$

S. Deshmukh, A. Basu, D. J. Schwarz (in prep)

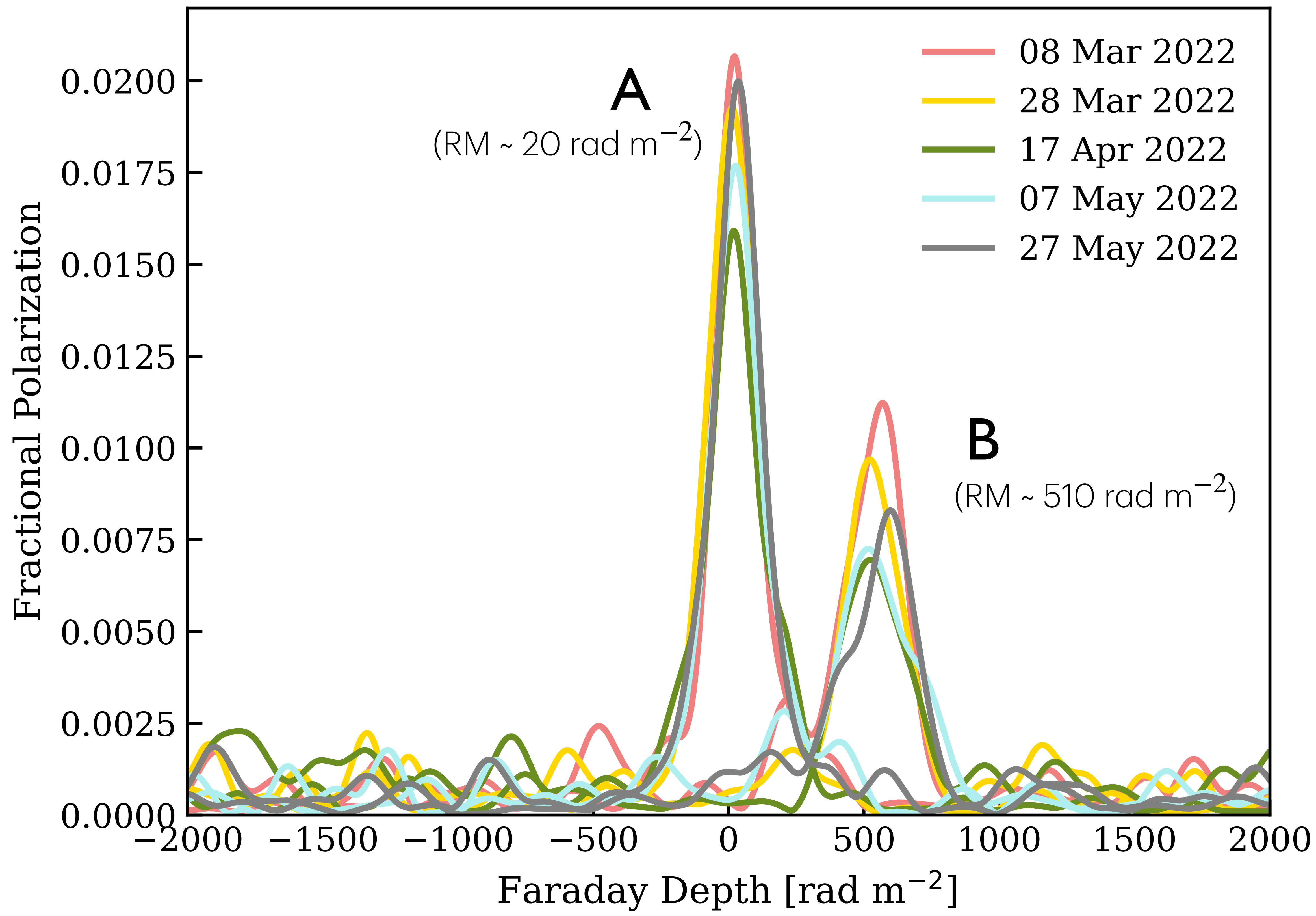
Rotation Measure (RM) synthesis

"Due to birefringence of the magneto-ionic medium, the polarization angle of linearly polarized radiation that propagates through the plasma is rotated as a function of frequency. This effect is called Faraday rotation."

M. A. Brentjens & A. G. de Bruyn 2005, A&A

- *Faraday rotation* $\propto \lambda^2$
- *Polarisation angle,* $\theta(\lambda^2) = \theta_0 + RM\,\lambda^2$

$$\theta_{\rm src} \equiv \theta_{\rm src}(t, \nu, {\rm RM}, \theta_0)$$



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Differential birefringence angle

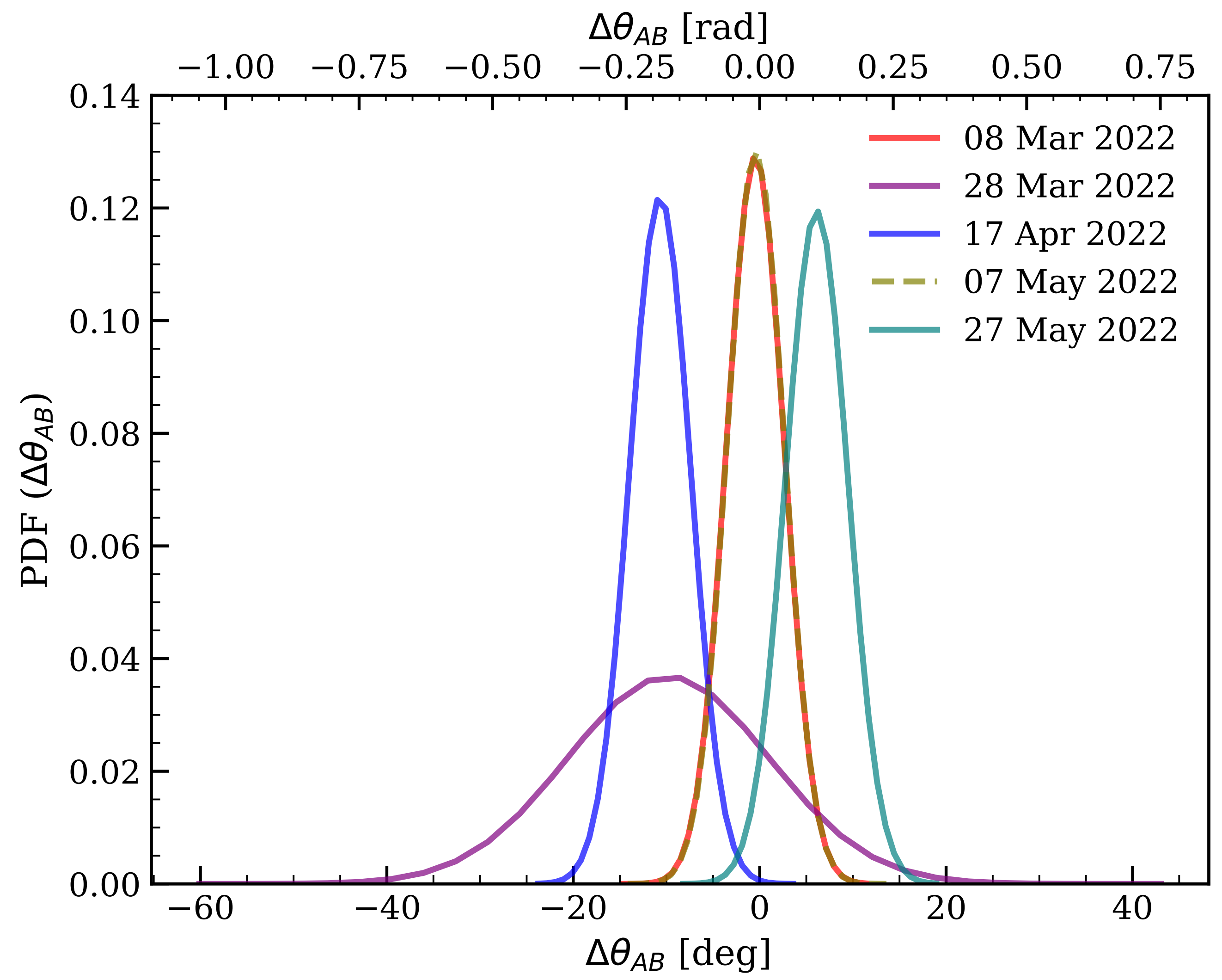
$$\Delta\theta_{\rm AB} = \underbrace{\theta_{\rm A}}_{\theta_{\rm src} + \delta\theta_{\rm ALP,\,A} + \delta\theta_{\rm cal}} - \underbrace{\theta_{\rm B}}_{\theta_{\rm src} + \delta\theta_{\rm ALP,\,B} + \delta\theta_{\rm cal}} = \delta\theta_{\rm ALP,\,A} - \delta\theta_{\rm ALP,\,B}$$

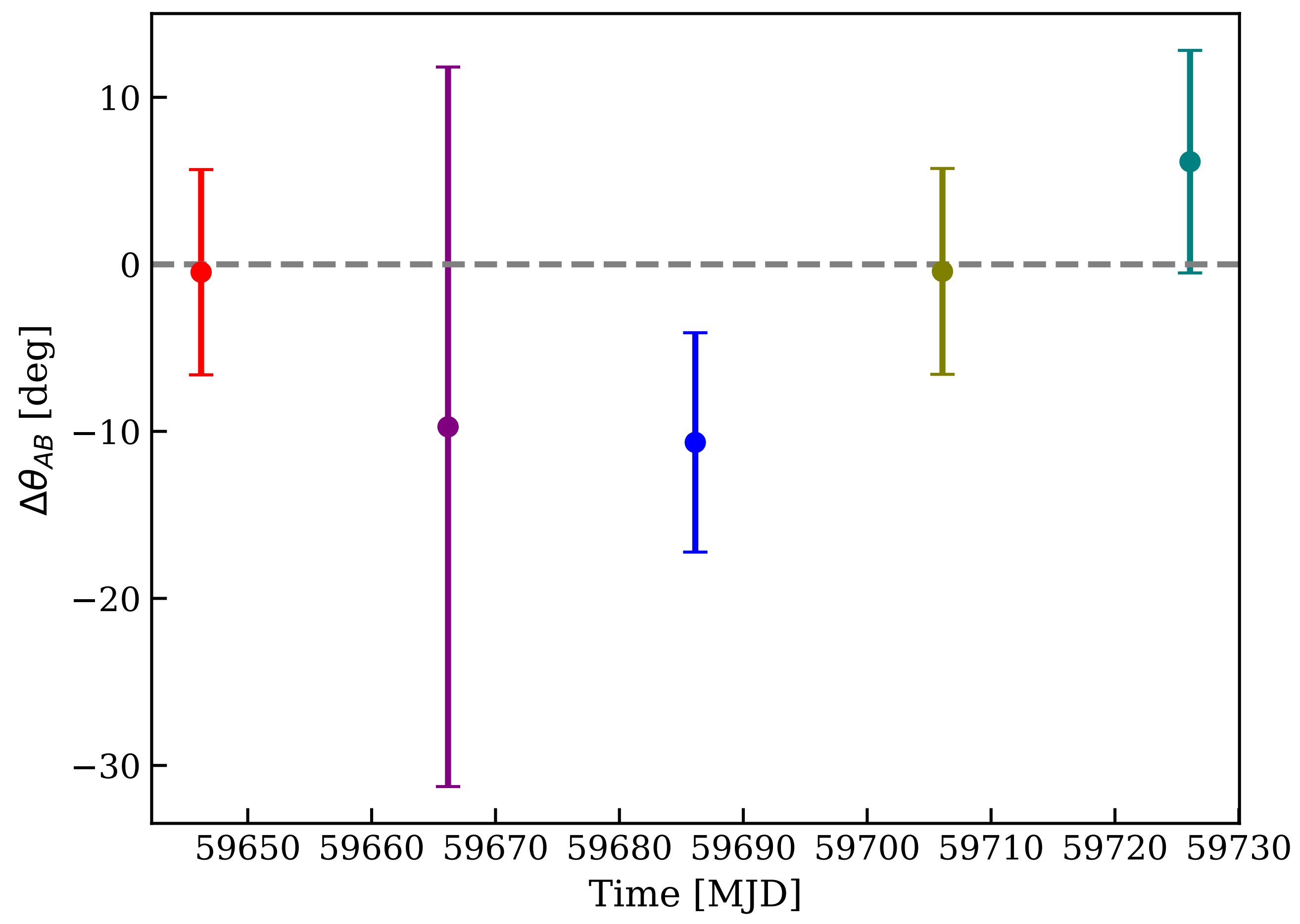
where $\theta_0 = \theta_{\rm src} - {\rm RM}\,\lambda^2$ & $\theta_{\rm src} = \frac{1}{2}\tan^{-1}\frac{U}{Q}$

$$\theta_{\rm src} \equiv \theta_{\rm src}(t, \nu, {\rm RM}, \theta_0)$$

Monte Carlo simulations for Q, U & RM

using 50,000 random samples (gaussian distribution with observed parameters)





$\Delta\theta_{\rm AB} = -1.525 \pm 3.151$ deg [95% CL]

$|\Delta\theta_{\rm AB}| \leq 4.676^\circ$

$\chi^2_{\rm dof} = 0.74$

Observations are in good agreement with null hypothesis

S. Deshmukh, A. Basu, D. J. Schwarz (in prep)

Exclusion region

95% confidence level

The constraints obtained with combined new and old observations are [at 95% CL]

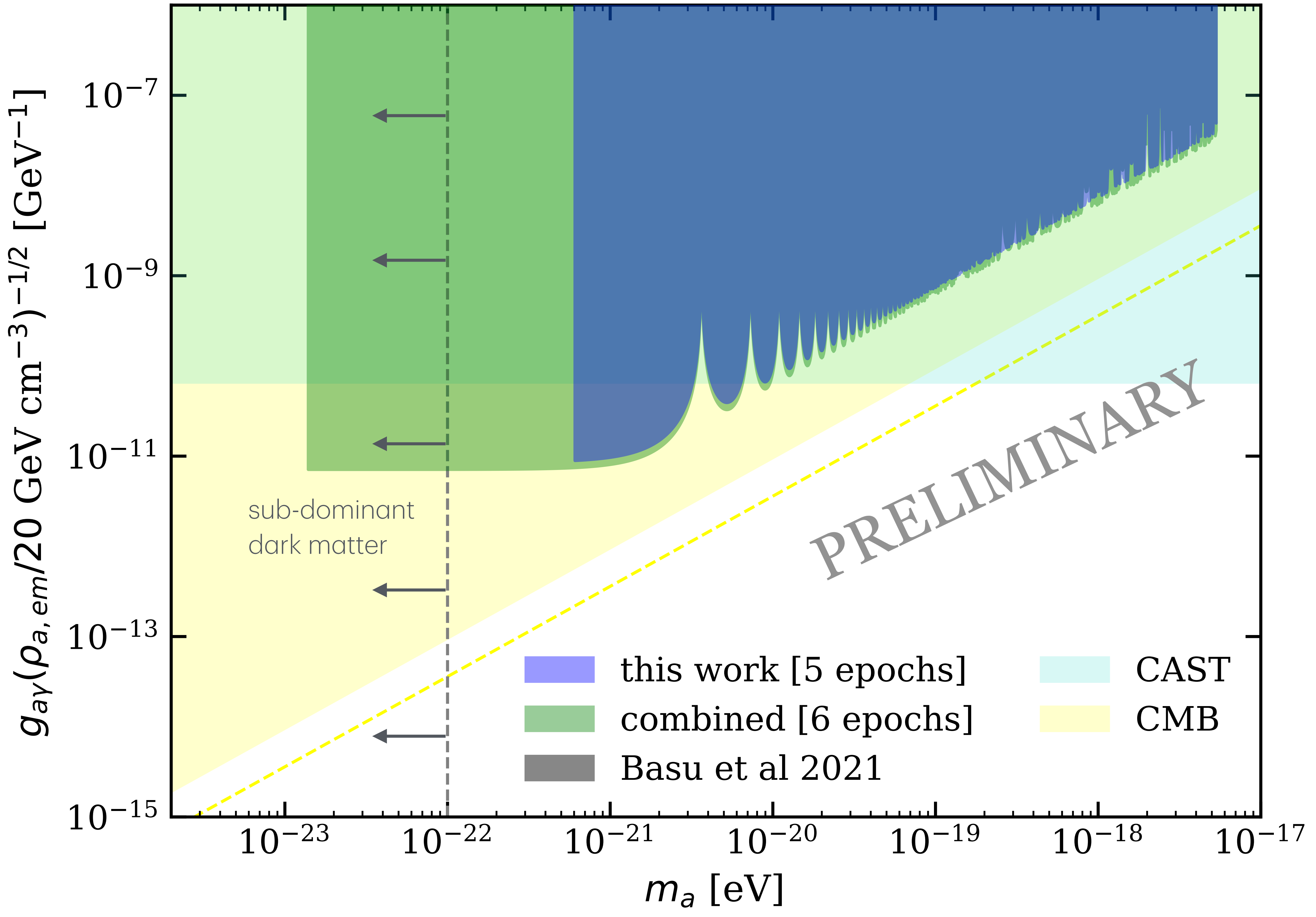
coupling

$$g_{a\gamma} \leq 1.5 \times 10^{-11} \left(\frac{20 \text{ GeV cm}^{-3}}{\rho_{a,\text{ em}}} \right) \text{GeV}^{-1}$$

$$\text{to} \quad 7.7 \times 10^{-8} \left(\frac{20 \text{ GeV cm}^{-3}}{\rho_{a,\text{ em}}} \right) \text{GeV}^{-1}$$

mass

$$1.5 \times 10^{-23} \text{ eV} \leq m_a \leq 4.6 \times 10^{-18} \text{ eV}$$



Statistically significant:

For a sample of N observations, our work demonstrates $\sim 1/\sqrt{N}$ improvement

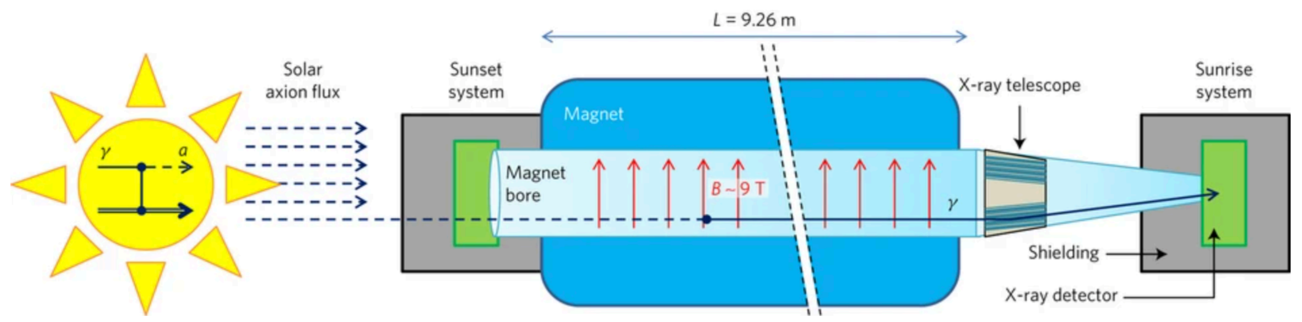


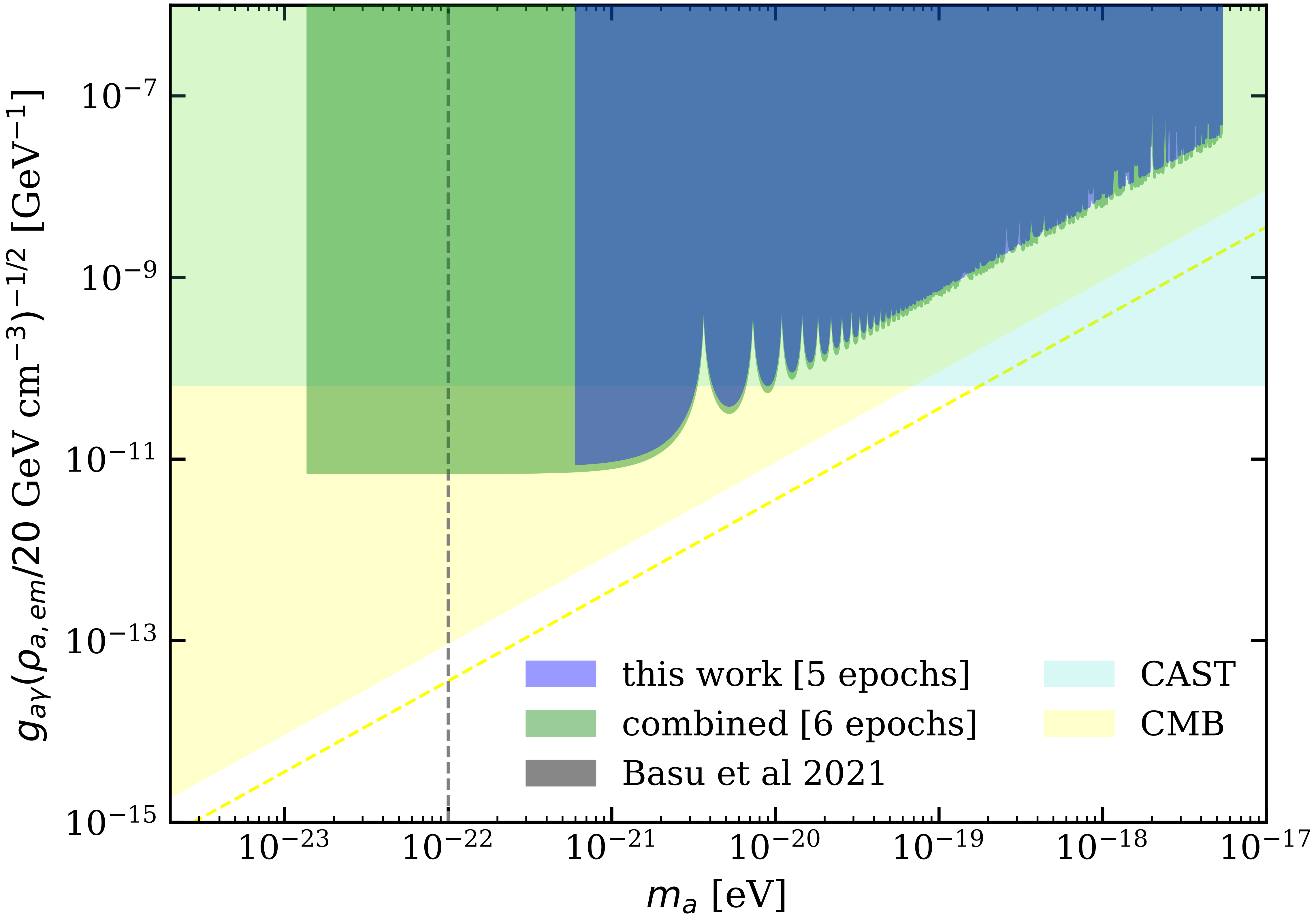
Image: CAST Collaboration

Already improved over CAST limit

S. Deshmukh, A. Basu, D. J. Schwarz (in prep)

Conclusion

- Strong gravitational lensing as a robust probe for Ultralight axion-like particles which is sensitive to both m_a and $g_{a\gamma}$
- The potential of realistically discovering ALPs using this method
- The differential polarisation angles from different lens systems can be combined to statistically improve the result
- Sensitivity comparable to lab-experiments
- **SKA-Mid AA*** (resolution ~0.3 arcsec) will allow us to probe significantly deeper parameter space and identify potential systematics.
- ***SKA-Mid AA4*** (resolution ~0.1 arcsec) will be a major player in constraining Ultralight axion-like particles



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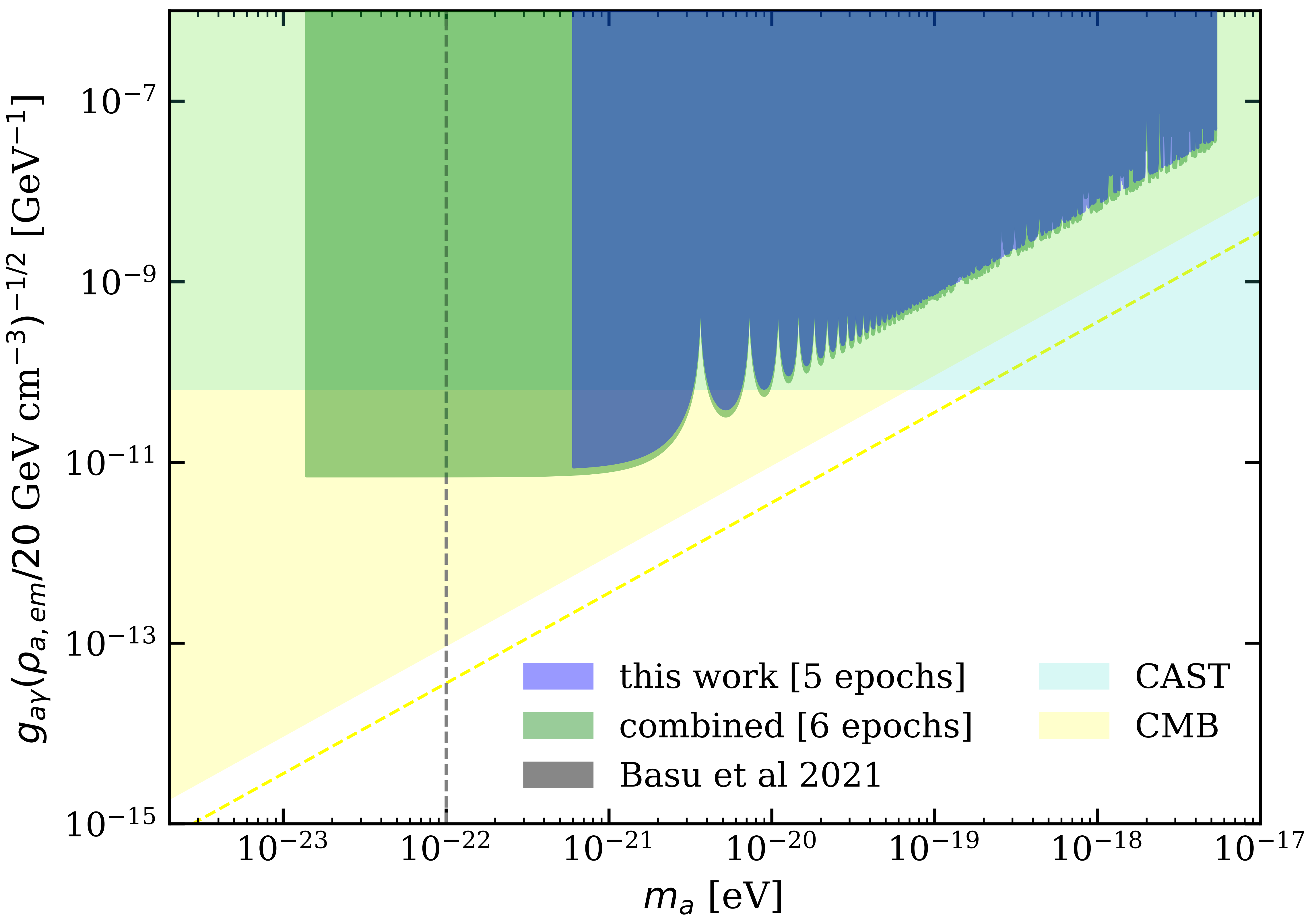

Thank you for your attention!