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# Inferring Line-of-Sight Velocity Distributions via Intensity Interferometry Correlation Functions

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# Kinematics in HBT

**Lab Observations:** HBT signal shape linked to source spectrum (see Gilles' Talk)

**Implications:** Since Doppler shifts alter spectrum
→ HBT encodes kinematics

Retrieve full information in 3D about system by studying both height/area and shape of $g^{(2)}$ peak

# Kinematics encoded in HBT

van Cittert-Zernike:

$$\Gamma(u_i, v_i; u_j, v_j) = \iint_{\text{source}} e^{-\frac{2\pi i}{\lambda}\left(\frac{u_i - u_j}{d} x + \frac{v_i - v_j}{d} y\right)} I(x,y)\, dx dy$$

usually temporal phase term treated as simple oscillation at single frequency

consider now Doppler effect

$$\nu = \nu_0 \left(1 + \frac{v_z}{c}\right)$$

$$\Gamma(u_i, v_i, t_i; u_j, v_j, t_j) = \iint_{\text{source}} e^{-\frac{2\pi i}{\lambda}\left(\boxed{\frac{u_i - u_j}{d} x + \frac{v_i - v_j}{d} y} + \boxed{v_z (t_i - t_j)}\right)} I(x,y)\, dx dy$$

not straightforward step, more detailed explanation in appendix of paper

# Glauber's Description

We are not reinventing the wheel…

in the original Glauber paper (1963, *The Quantum Theory of Optical Coherence*):

To discuss the general form which the field correlation functions take in such states it is convenient to abbreviate a set of coordinates $(\mathbf{r}_j, t_j)$ by a single symbol $x_j$. The $n$th-order correlation function is then defined as[3]

$$G_{\mu_1 \cdots \mu_{2n}}{}^{(n)}(x_1 \cdots x_{2n}) = \mathrm{tr}\{\rho E_{\mu_1}{}^{(-)}(x_1) \cdots \times E_{\mu_n}{}^{(-)}(x_n) E_{\mu_{n+1}}{}^{(+)}(x_{n+1}) \cdots E_{\mu_{2n}}{}^{(+)}(x_{2n})\}. \quad (10.2)$$

# Simulation Framework

Simulating kinematic systems using particle populations:

- Generate population of *k* amount of particles, with suitable position and velocity vectors
- Create 2D projection onto sky plane and determine LoS velocities
- Use discrete version of previously shown integral:

$$|V_{12}(u,v,t)|^2 = \left| \left\langle \exp\left[ 2\pi i \left( \frac{u \cdot x_k + v \cdot y_k}{\lambda\, d} + \frac{v_{\mathrm{LoS},k}}{\lambda}\, t \right) \right] \right\rangle_k \right|^2$$

# Case Study I: γ Cas

## Choice and Parameters

Already been/being studied using SII

Decretion disk with $H_\alpha$ emission line

| | |
|---|---|
| Distance | 168 pc (Hutter et al. 2021) |
| Mass of central star | 13 $M_\odot$ (Hutter et al. 2021) |
| Radius of central star | 10 $R_\odot$ (ESA 1997) |
| Outer Radius of disk | 14 AU (Stee et al. 2012) |
| Wavelength | 656 nm |
| Particles | $3 \cdot 10^6$ |

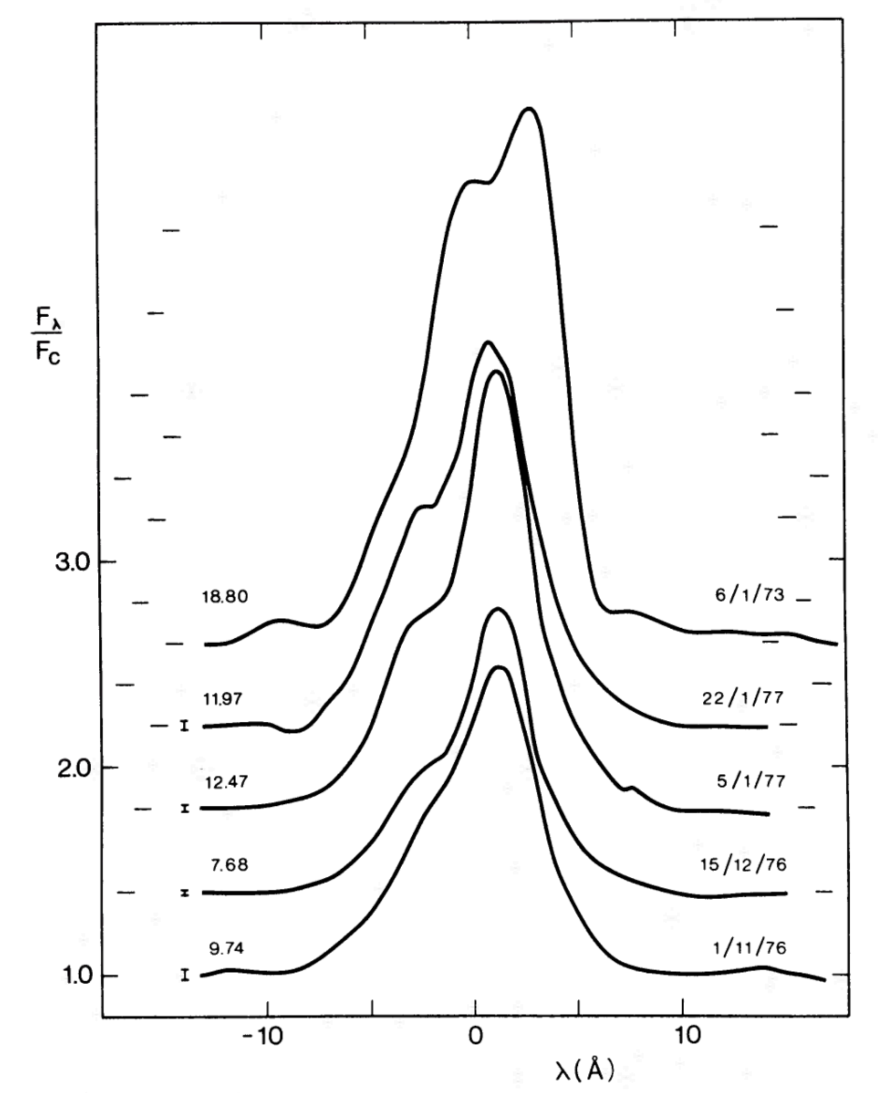
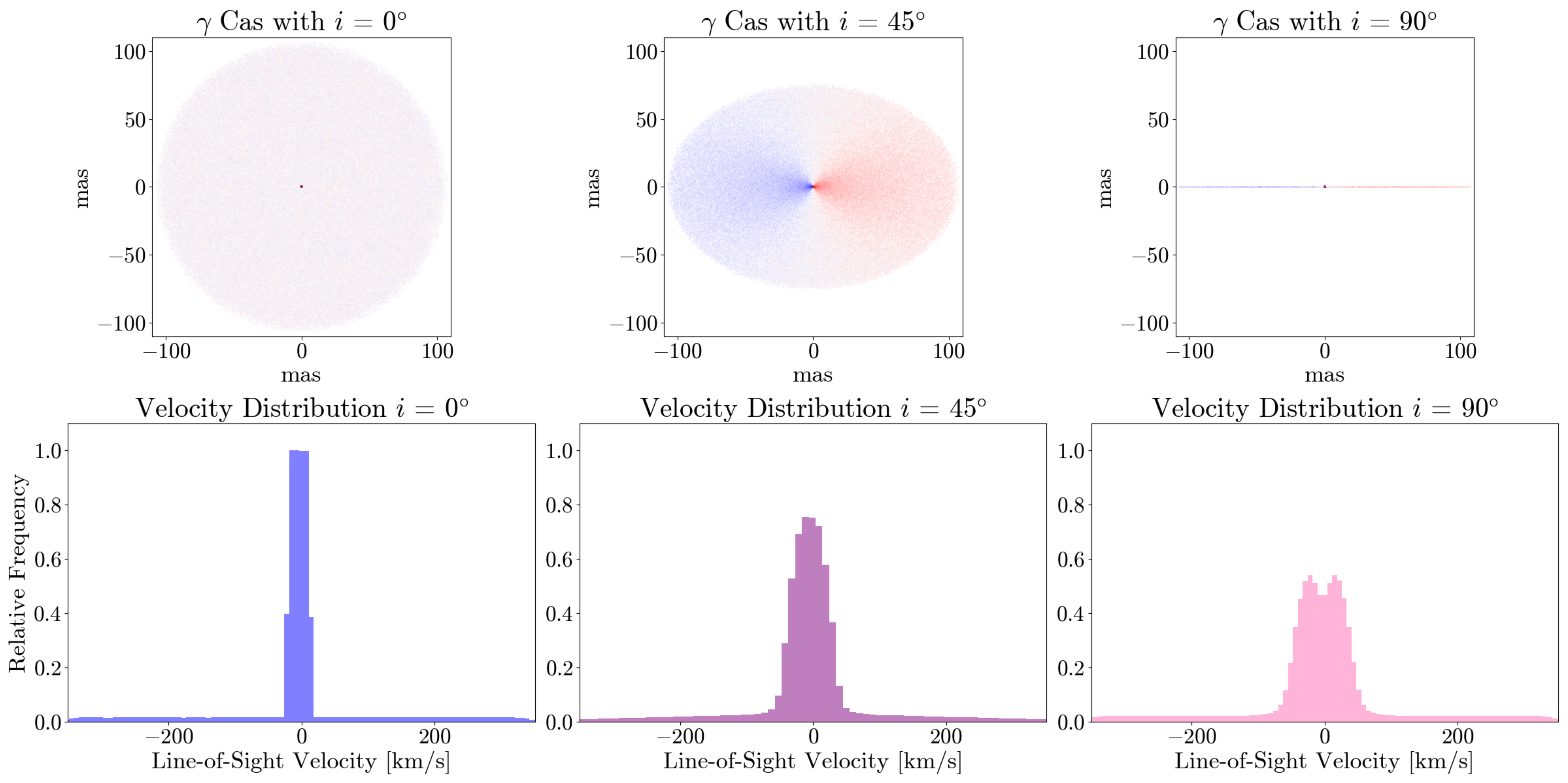



FIG. 4.—Hα line profiles for γ Cas. All profiles are on the same scale. However, relative wavelength positions are uncertain. The number on the left is the equivalent width (in Å). The date is on the right. The top profile is taken from Gray and Marlborough (1974). The error bars on the left represent the standard deviation of the mean for a 3 Å interval in the continuum.

R. Poeckert and J. M. Marlborough, *A Model for Gamma Cassiopeiae.*, The Astrophysical Journal **220**, 940 (1978)

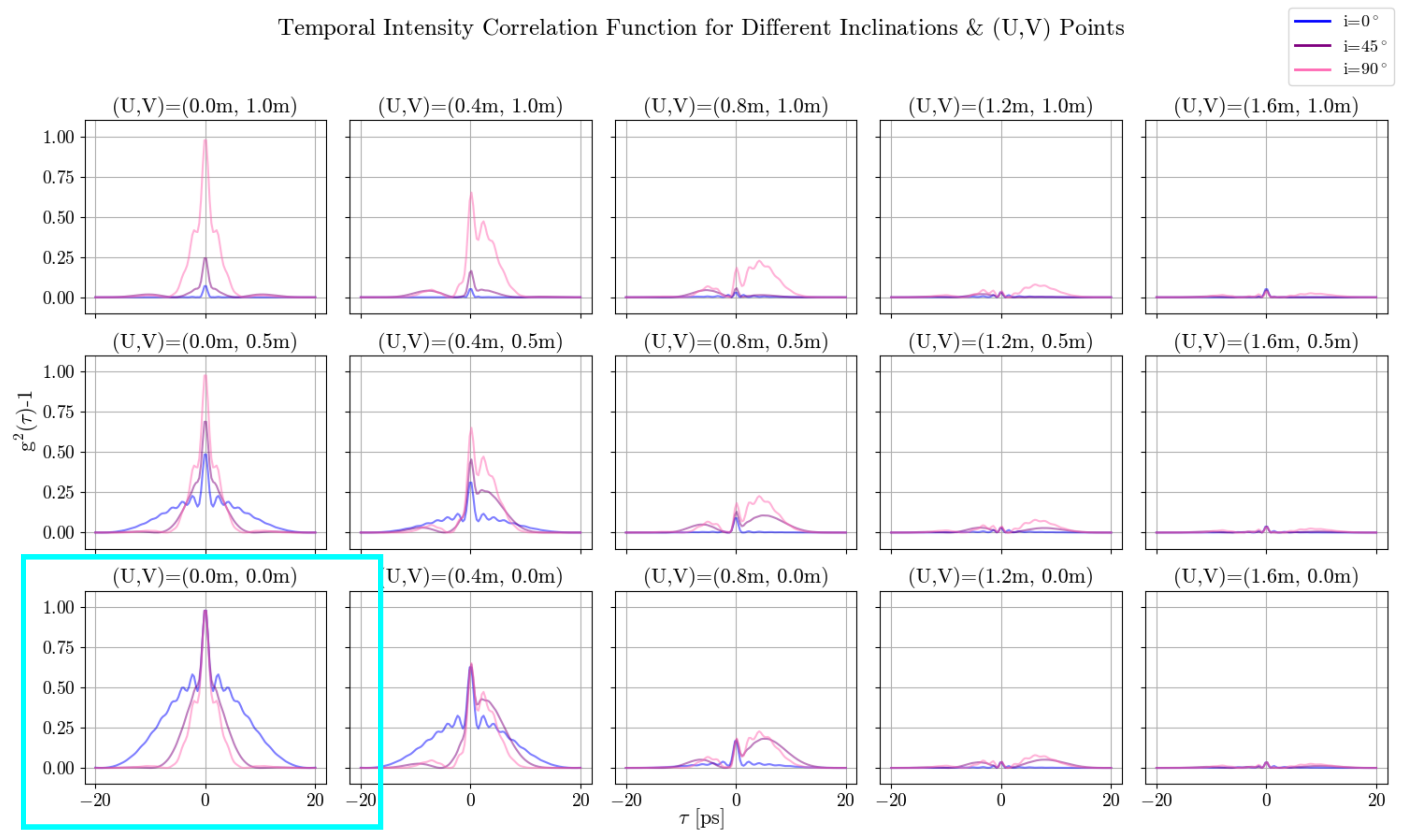
# Case Study I: γ Cas

## Results



# Case Study I: γ Cas

## Results



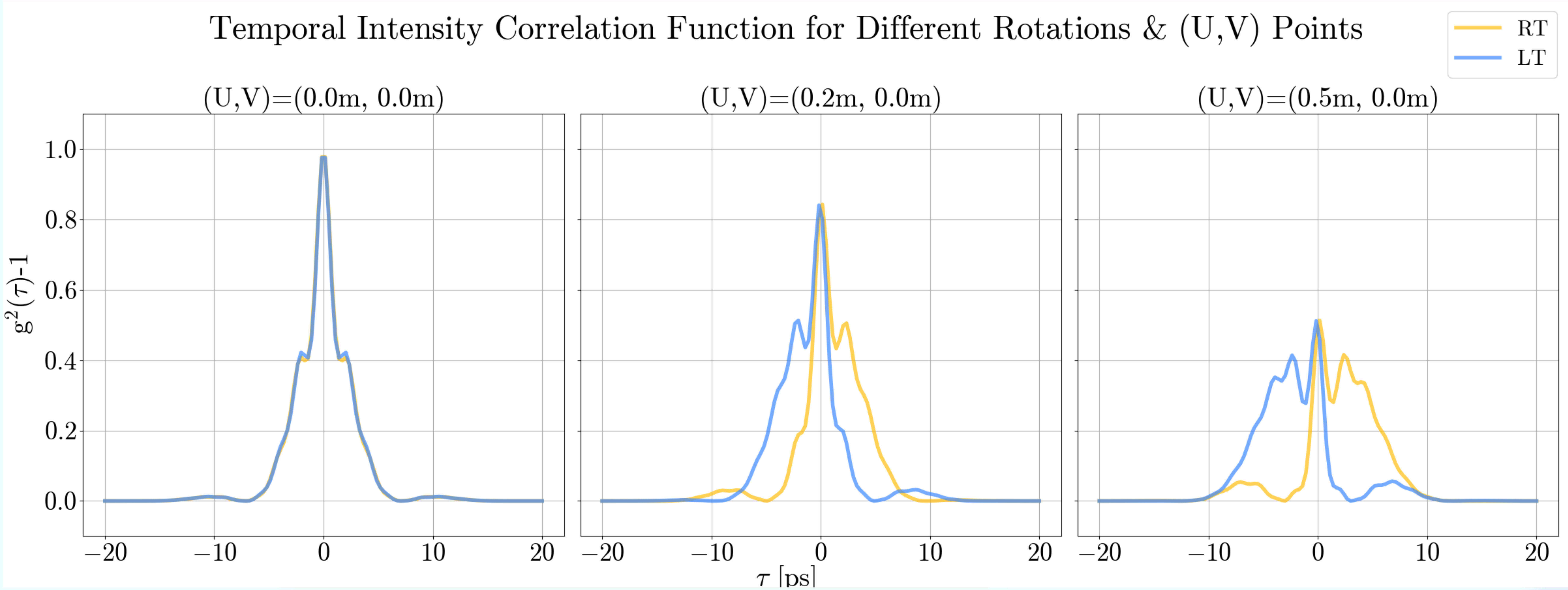

**Inclination angle dependence:**
Edge on → narrower peak (broader velocities)

**Time Asymmetry:**
Peak shifts form τ=0 for rotating systems

**Rotation direction:**
Sign of shift reveals rotation sense

# Case Study I: γ Cas

## Results



# Case Study II: γ Per

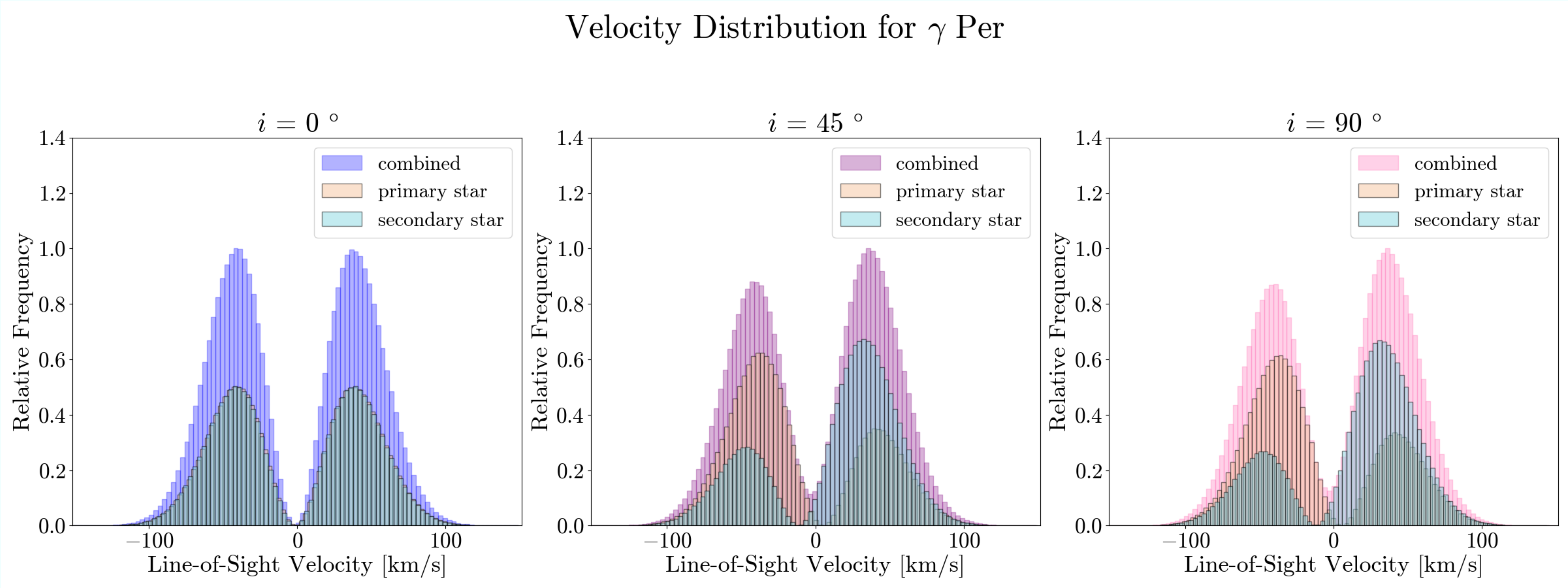
## Choice and Parameters

Binary star system with absorption line

| | |
|---|---|
| Distance | 68 pc (Ling et al. 2001) |
| Mass of primary star | 3.6 $M_\odot$ (Diamant et al. 2023) |
| Radius of primary star | 22.7 $R_\odot$ (Diamant et al. 2023) |
| Mass of secondary star | 2.4 $M_\odot$ (Diamant et al. 2023) |
| Radius of secondary star | 3.9 $R_\odot$ (Diamant et al. 2023) |
| Semi-major axis | 9.6 AU (Ling et al. 2001) |
| Wavelength | 393 nm |
| Particles | $3 \cdot 10^6$ |

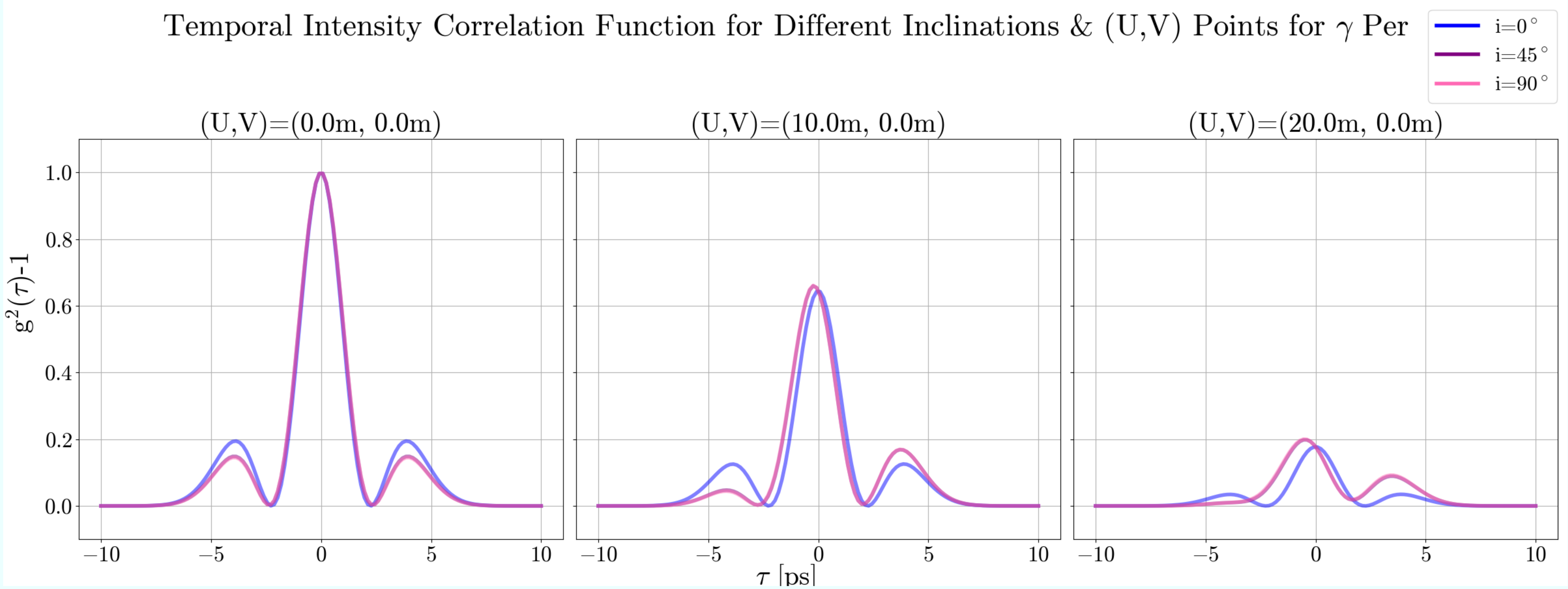
# Case Study II: γ Per

## Results



# Case Study II: γ Per

## Results




**Inclination angle dependence:** More subtle than in decretion disk case

# Velocity Dependence

Coherence time: $\Delta\tau = \frac{\lambda^2}{c\,\Delta\lambda}$

Doppler Shift: $\frac{\Delta\lambda_{\rm kin}}{\lambda} = \frac{v}{c}$

Assume $\Delta t < \Delta\tau$ and $\Delta\lambda_{\rm kin} < \Delta\lambda$ → $\frac{v}{c} < \frac{\Delta\lambda}{\lambda} < \frac{\lambda}{c\,\Delta t}$

with $\Delta t$ ~10ps, assuming optical wavelengths and sources with $v$ ~10km/s, one needs $\Delta\lambda$ to be sub-nm

# Conclusions & Outlook

**New observable:**

Time-asymmetric HBT effect links stellar kinematics to temporal correlations

**Demonstrated through simulations:**

signatures of both inclination and rotation in HBT peak

**Key advantage:**

Complementary to spectroscopy with counter intuitive advantage

**Outlook:**

- Inversion problem remains unsolved
- Lab experiments to test and validate this effect
- Reaching the time resolution regime necessary but feasible

# Thank you, and have a safe trip home!

An interesting read for your trip home :)

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Calern Nov ’24

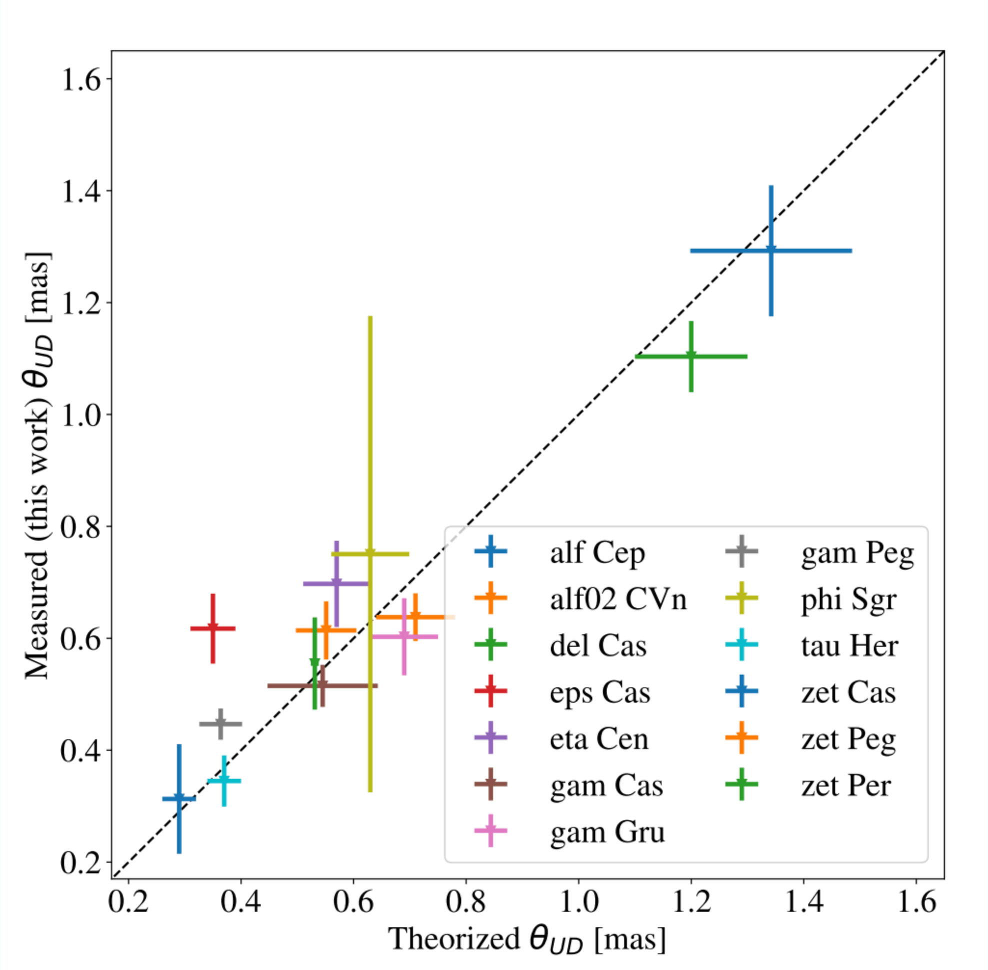
# Back-Up

# From Static to Dynamic Systems

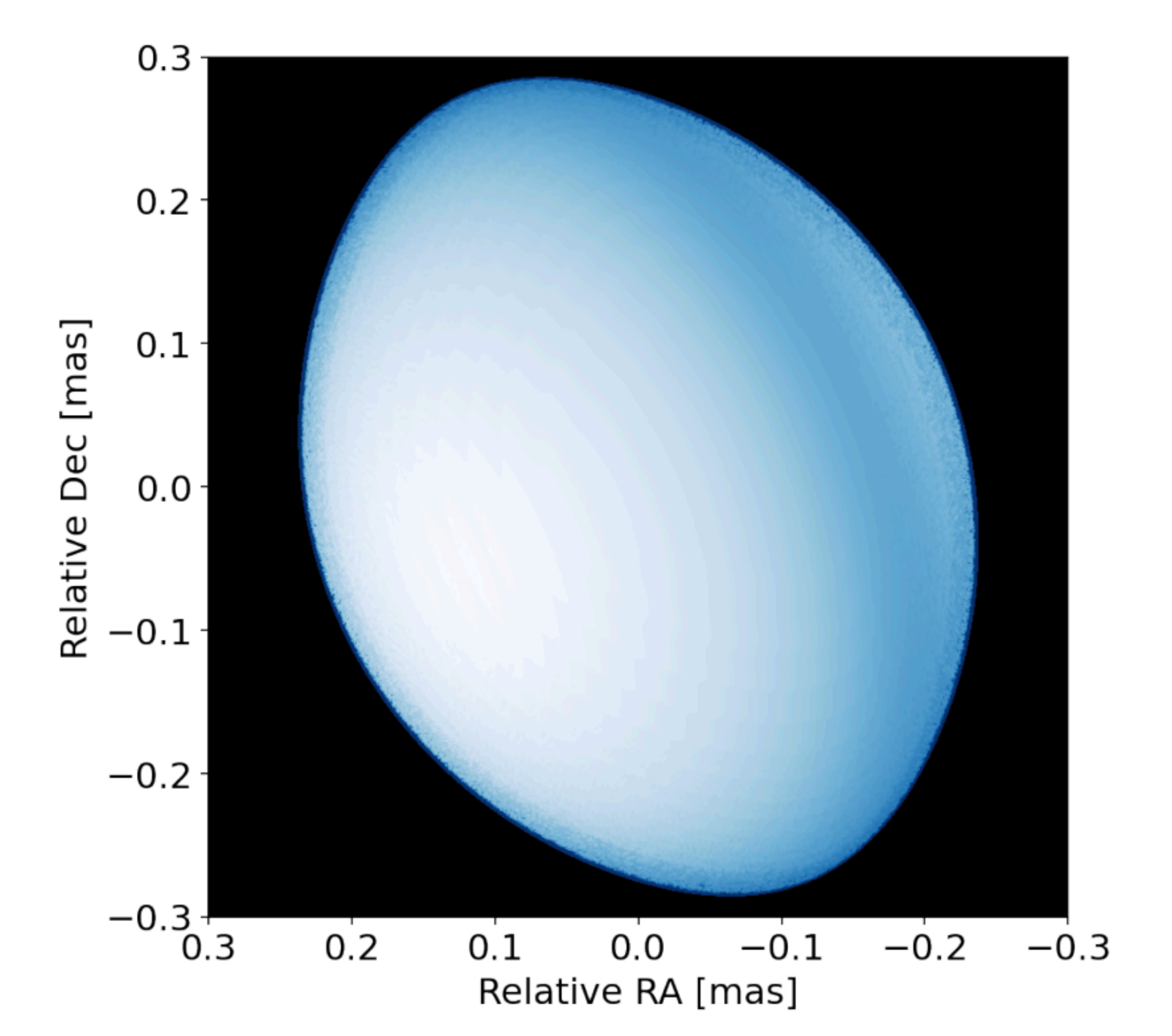
SII has been successfully revived this century

Diameters can be measured, confirmed or used as calibration

Moving from quasi static to dynamic targets
Fast Rotators, Binaries




MAGIC, MNRAS **529**, 4387 (2024)




VERITAS, arXiv:2506.15027

# Explanation with Speckles

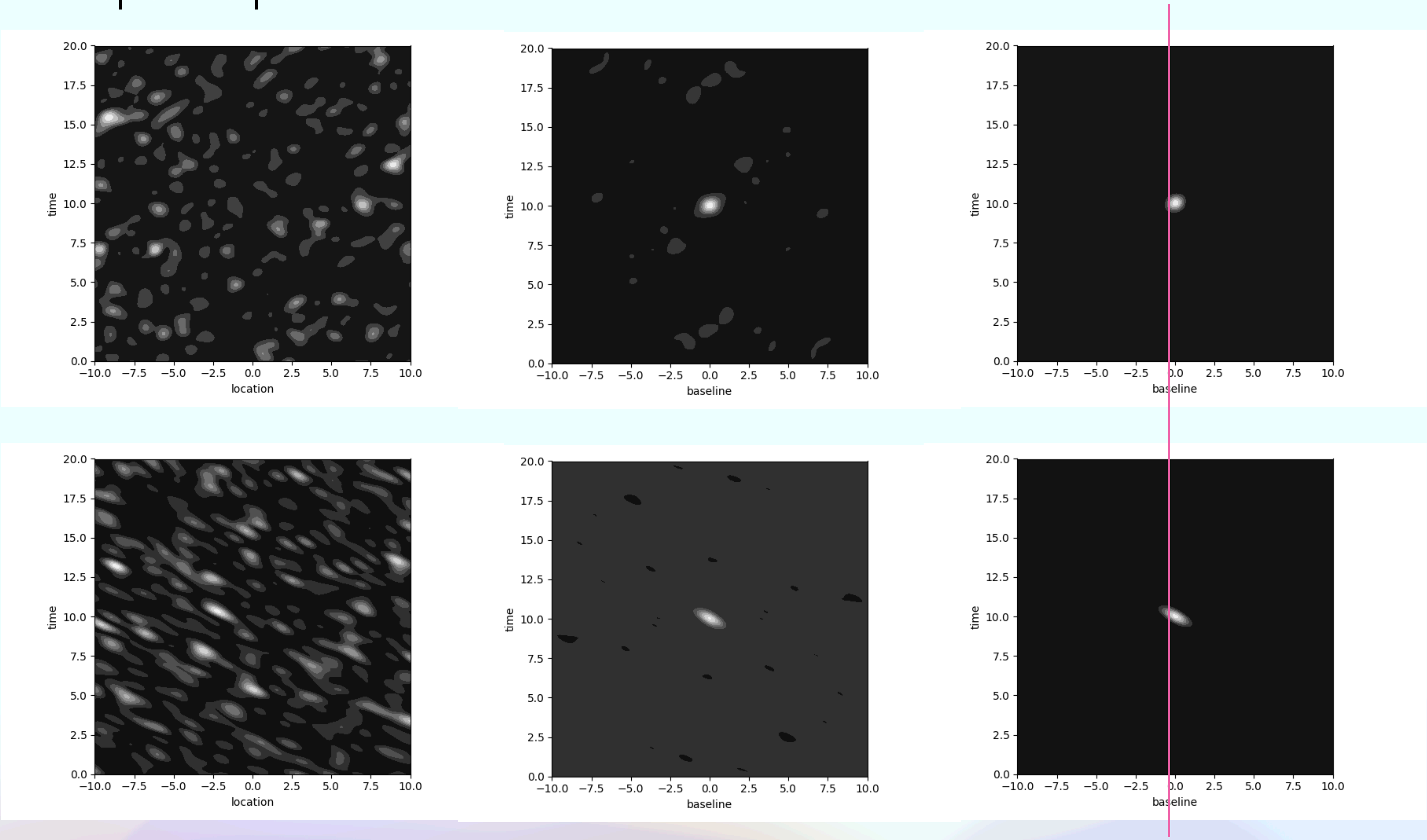
raw intensity speckle pattern

autocorrelation

squared visibility

static/symmetric

rotating/asymmetric



# Velocity Dependence

| $\lambda$ [nm] | v [km/s] | ~$\Delta\lambda$ [nm] | ~$\Delta\tau$ [ps] |
|---|---|---|---|
| 656 | 1 | 0.002 | 700 |
| | 10 | 0.02 | 70 |
| | 100 | 0.2 | 7 |
| | 1000 | 2 | 0.7 |

Slow motion → larger $\Delta\tau$ → easier to measure

Fast motion → smaller $\Delta\tau$ → harder to measure