Capabilities of future intensity interferometers

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Collège de France &
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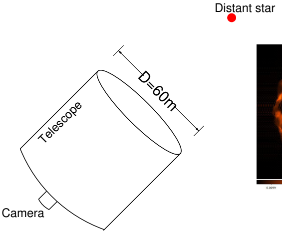
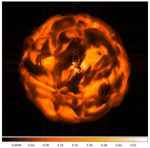
Talk outline

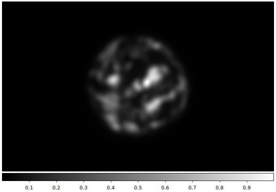
- Intro: point of view of amplitude interferometry
- Interferometry in terms of correlations
- Cherenkov Telescope Arrays for Intensity Interferometry
- Imaging strategies with Intensity Interferometry
- Fast Rotating Be stars
  (In collab. with A. Domiciano de Souza)
- Conclusions

Interferometers as Dilute Telescopes

Simulation example: Betelgeuse at $\lambda = 710\,\mathrm{nm}$ (No turbulence)







$\sim 30\,\mathrm{mas}$

Angular resolution: $\Delta\theta \sim \lambda/D$ (Pristine image by A. Chiavassa)

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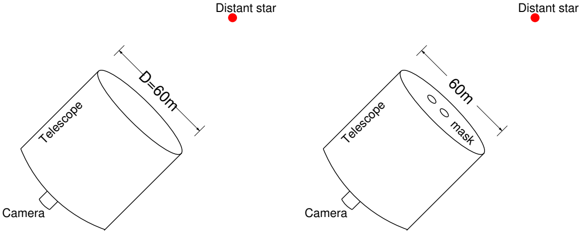

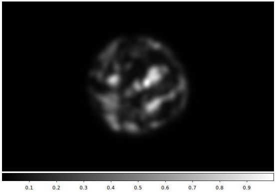

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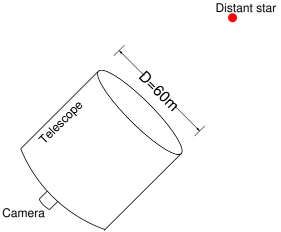

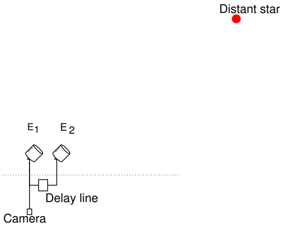

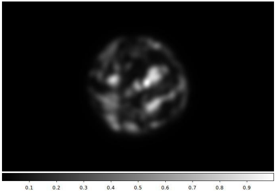

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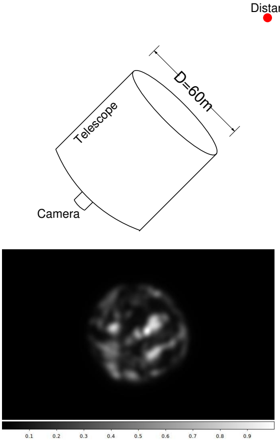

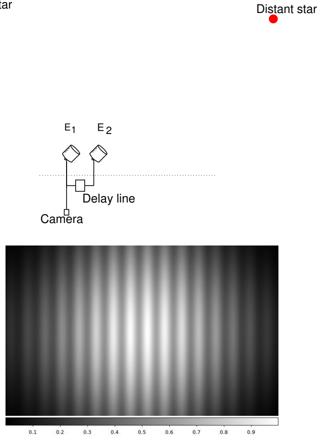

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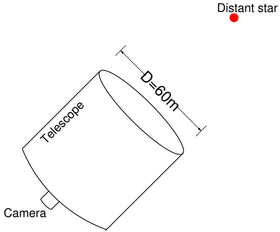
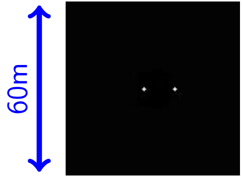
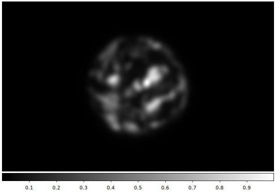
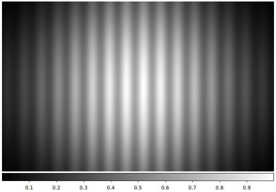




2 apertures





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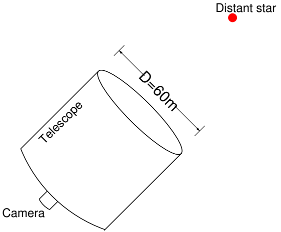
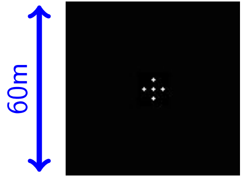
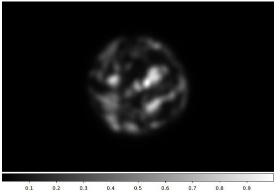




5 apertures



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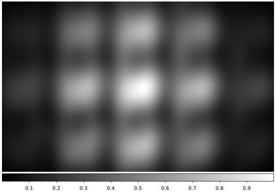

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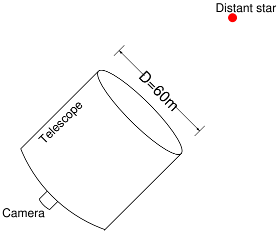
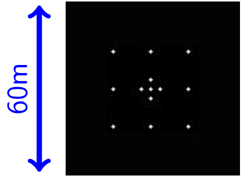
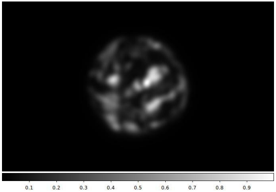
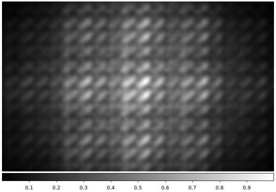




13 apertures





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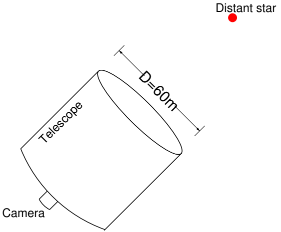
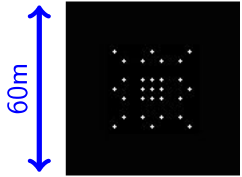
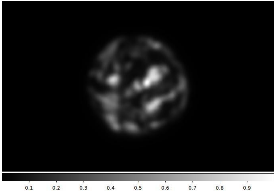




29 apertures



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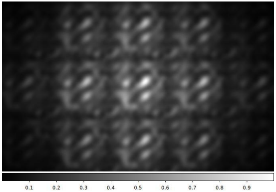

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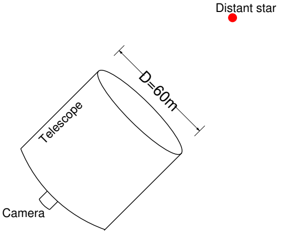
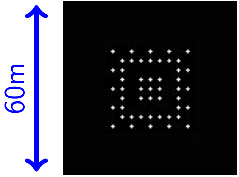
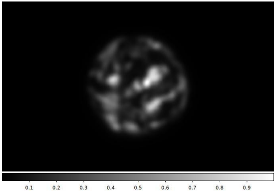




49 apertures



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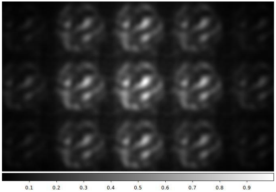

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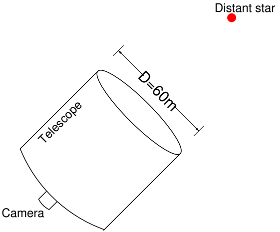
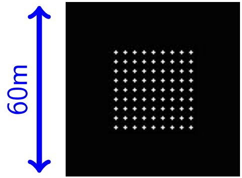
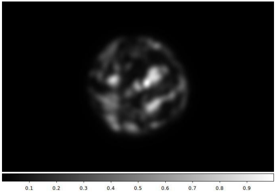
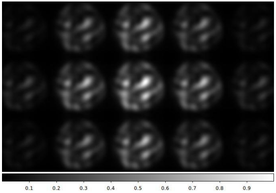




81 apertures





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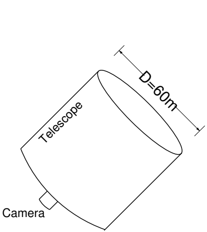
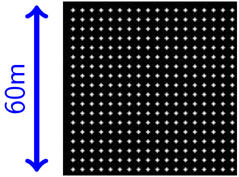
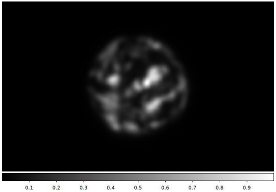
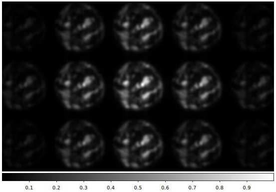




324 apertures





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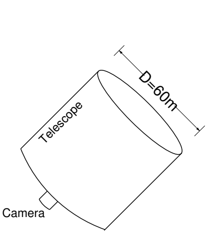
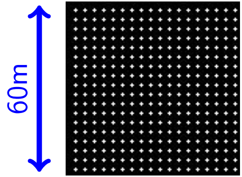
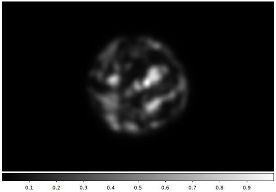




324 apertures



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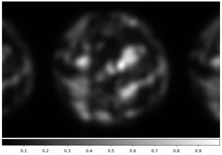

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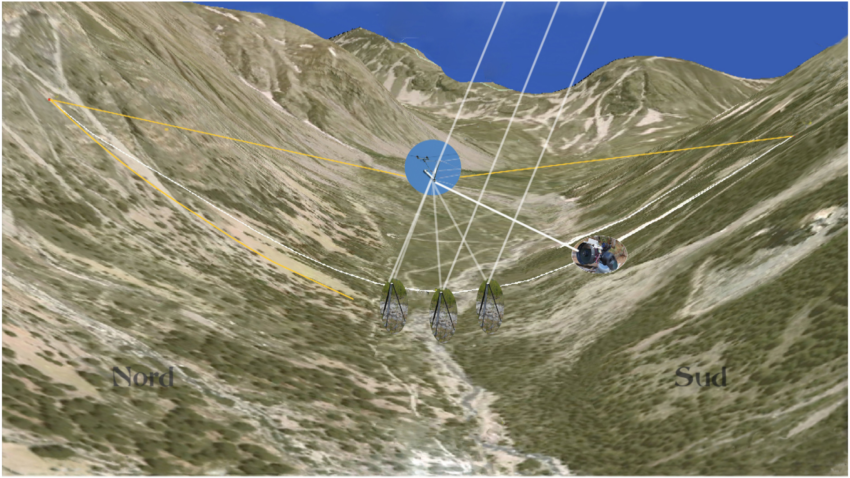
A proposed solution: The Hypertelescope (A. Labeyrie)

Prototype under construction in a high alpline valley



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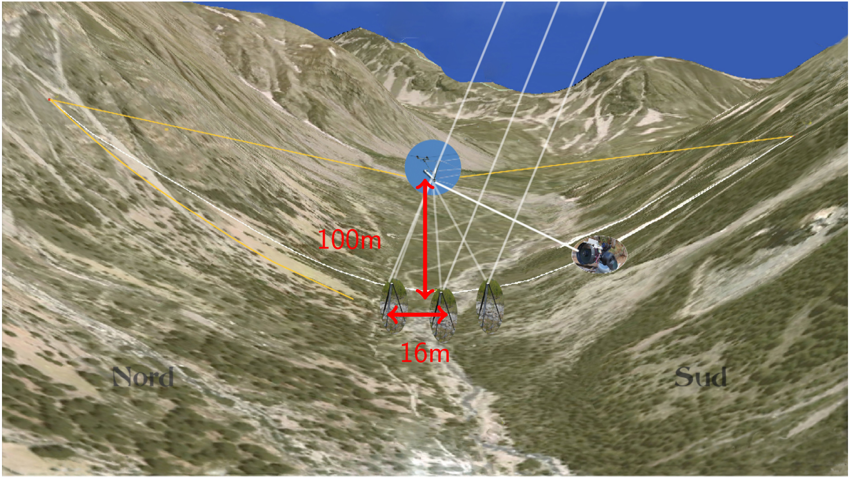

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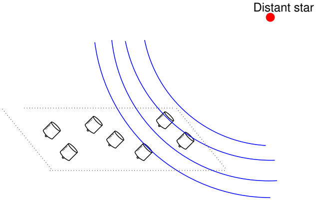
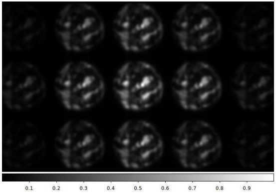
A challenge: Wave-front errors

Simulated Example: **atmospheric** turbulence





A challenge: Wave-front errors

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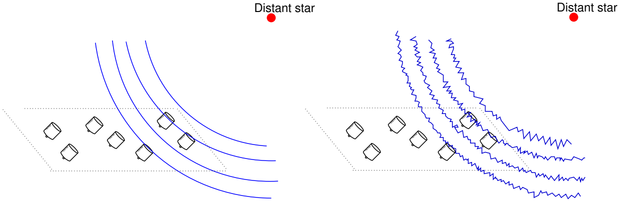

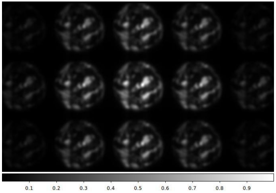

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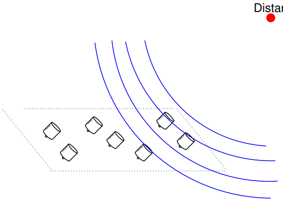

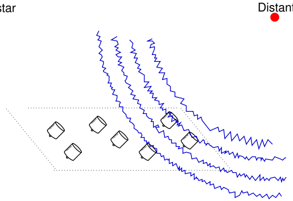

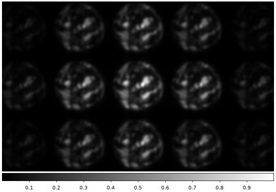

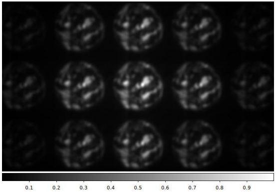

$\lambda/10$

A challenge: Wave-front errors

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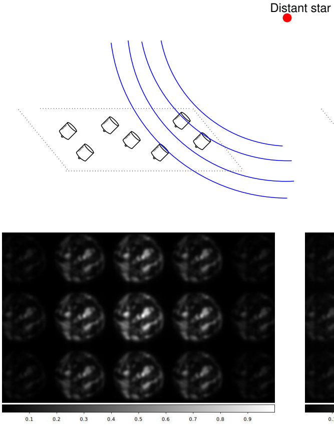

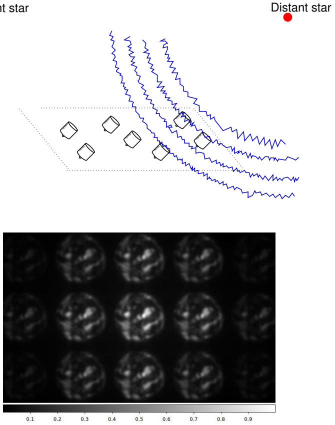

$\lambda/9$

A challenge: Wave-front errors

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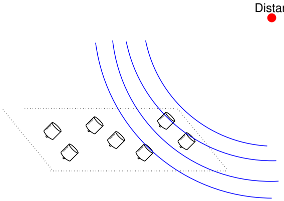

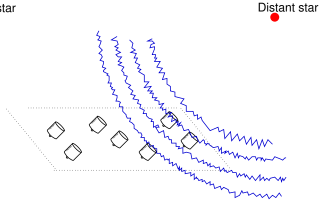

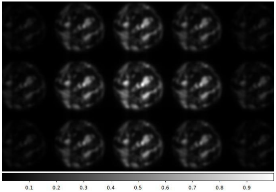

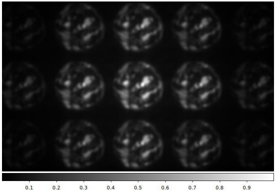

$\lambda/8$

A challenge: Wave-front errors

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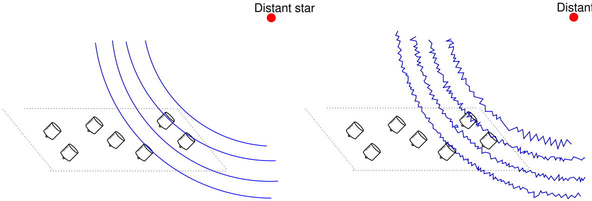

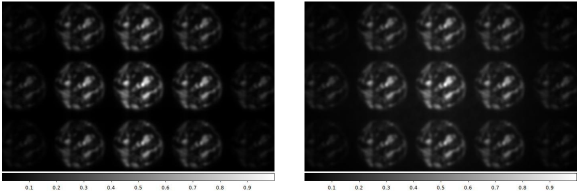

$\lambda/7$

A challenge: Wave-front errors

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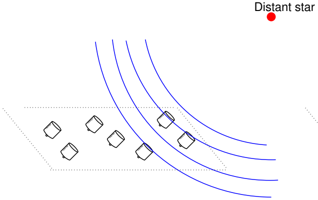

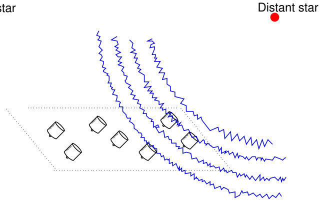

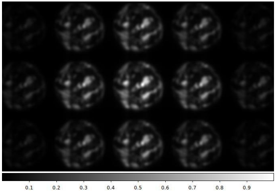

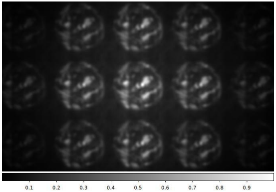

$\lambda/6$

A challenge: Wave-front errors

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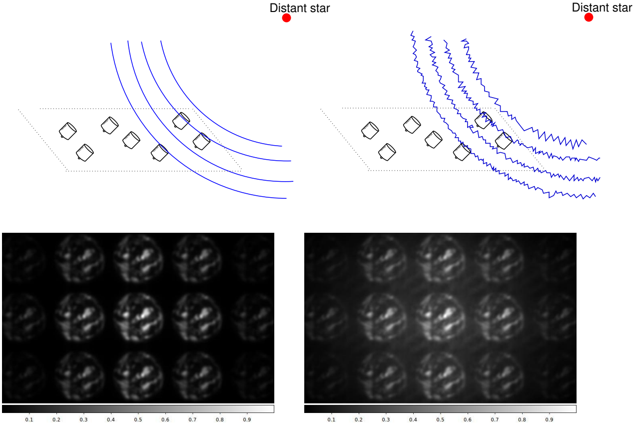
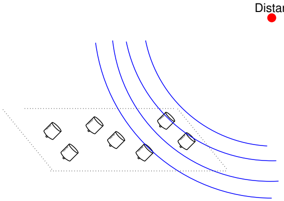
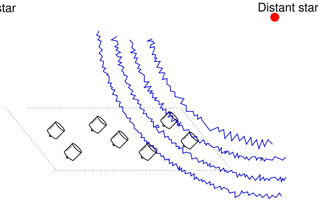


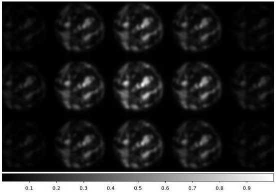
$\lambda/5$

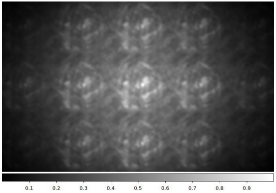
A challenge: Wave-front errors

Simulated Example: **atmospheric** turbulence





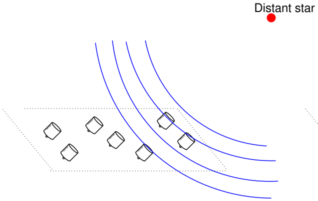


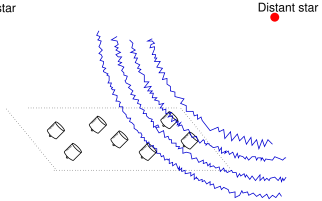


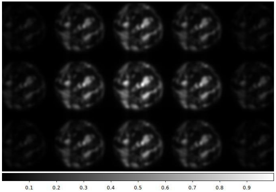
$\lambda/4$

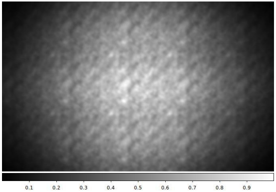
A challenge: Wave-front errors

Simulated Example: **atmospheric** turbulence





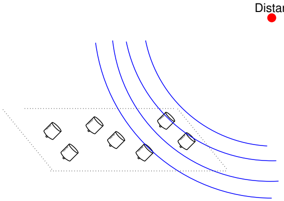


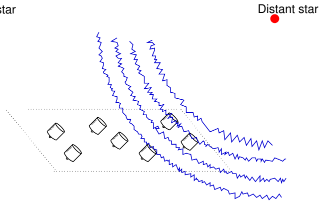


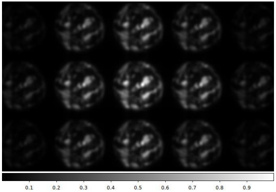
$\lambda/3$

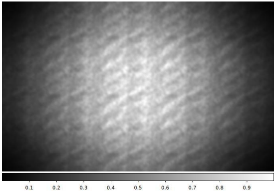
A challenge: Wave-front errors

Simulated Example: **atmospheric** turbulence





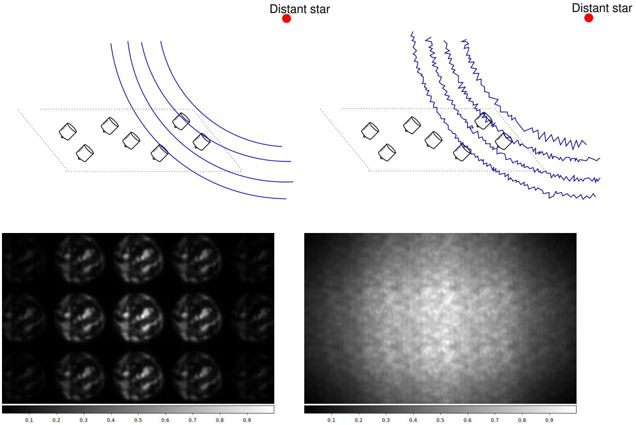




$\lambda/2$

A challenge: Wave-front errors

Simulated Example: **atmospheric** turbulence



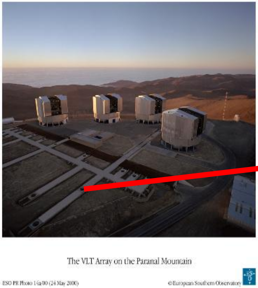
λ

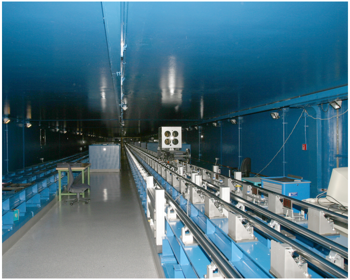
Challenges of amplitude interferometry

- Atmospheric turbulence limits the exposure time.

$\Rightarrow$ Short (ms) exposures ($m < 10$).

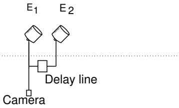
- Need to construct a large instrument with sub-wavelength precision
  - Optical delay lines.

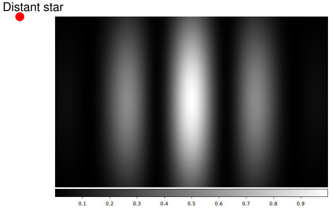




There are proposals to have Laser-Guide-Stars (Nuñez, Labeyrie, Riaud, 2014)

Interpretation in terms of correlations

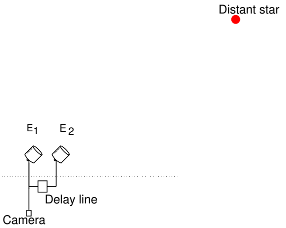


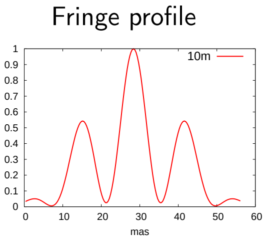


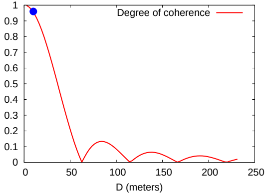
$$\left\langle |E_1 + E_2|^2 \right\rangle = \left\langle |E_1|^2 \right\rangle + \left\langle |E_2|^2 \right\rangle + 2\, Re \underbrace{\left\langle E_1^* \cdot E_2 \right\rangle}_{Correlation}$$

Correlation $\Leftrightarrow$ Contrast $\Leftrightarrow$ Fourier Tr. of star ($\mathcal{F}[\mathcal{O}(\theta)] = \tilde{\mathcal{O}}(x)$)

Interpretation in terms of correlations







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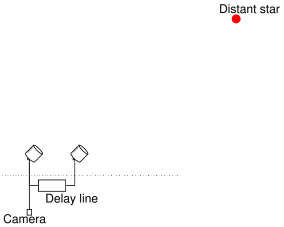

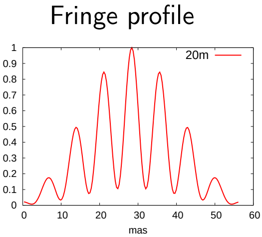

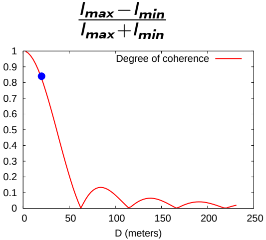

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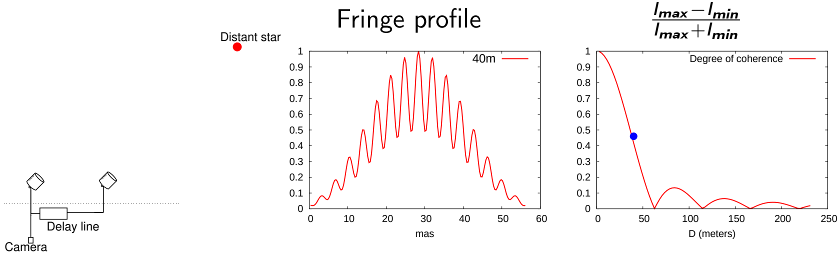

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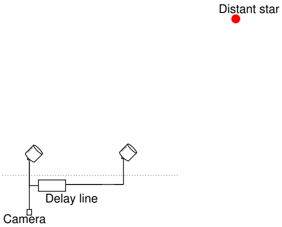

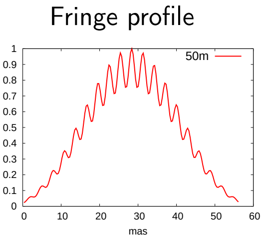

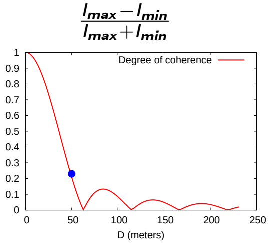

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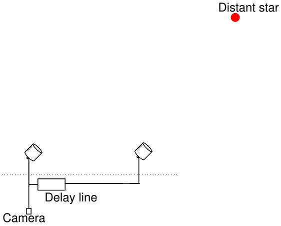

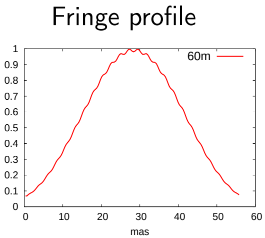

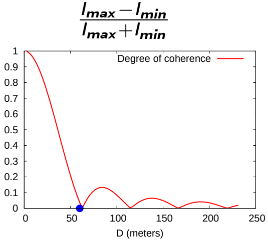

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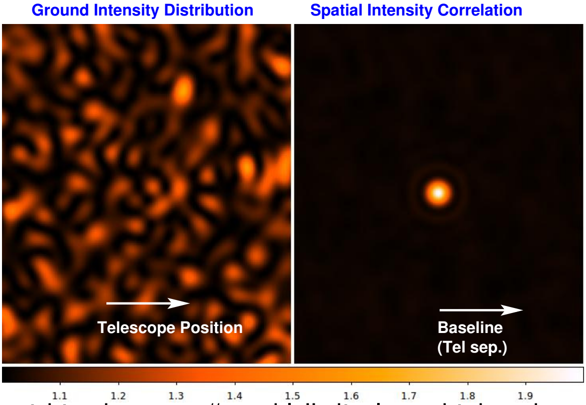
Correlation $\Leftrightarrow$ Contrast $\Leftrightarrow$ Fourier Tr. of star $(\mathcal{F}[\mathcal{O}(\theta)] = \tilde{\mathcal{O}}(x))$

A Speckle Interpretation of Stellar Intensity Interferometry

The intensity distribution on the ground is a speckle-pattern that changes at a timescale of $\tau \sim \lambda^2/(c\Delta\lambda)$.

Example: A uniform disk-like star



Detectors within the same “speckle” display a higher degree of mutual correlation

Information contained in intensity correlations

Amplitude interferometry allows measuring the complex degree of coherence γ

$$\gamma(r_i, t_i; r_j, t_j) \equiv \frac{\langle E^*(r_i, t_i) \cdot E(r_j, t_j) \rangle}{\sqrt{\langle |E^*(r_i, t_i)|^2 \rangle \langle |E^*(r_j, t_j)|^2 \rangle}}$$

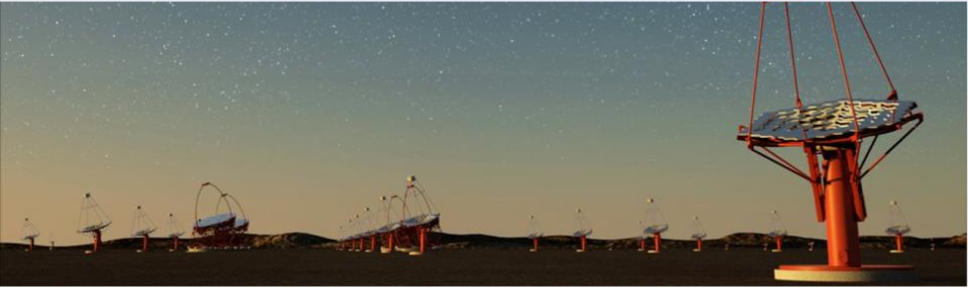
Two-point Intensity correlations allow measuring its square modulus

$$\frac{\langle I_i I_j \rangle}{\langle I_i \rangle \langle I_j \rangle} = 1 + |\gamma_{ij}|^2$$

Three-point Intensity correlations retain some phase information

$$\frac{\langle I_i I_j I_k \rangle}{\langle I_i \rangle \langle I_j \rangle \langle I_k \rangle} = 1 + |\gamma_{ij}|^2 + |\gamma_{jk}|^2 + |\gamma_{ki}|^2 + 2Re \underbrace{[\gamma_{ij}\gamma_{jk}\gamma_{ki}]}_{|\gamma_{\boldsymbol{ij}}||\gamma_{\boldsymbol{jk}}||\gamma_{\boldsymbol{ki}}| \exp i(\phi_{\boldsymbol{ij}}+\phi_{\boldsymbol{jk}}+\phi_{\boldsymbol{ki}})}$$

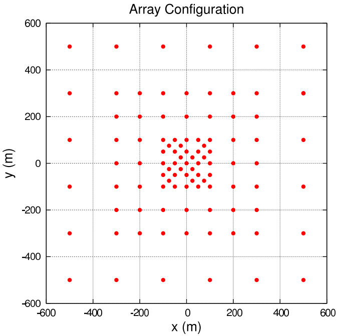
Air Cherenkov telescope arrays

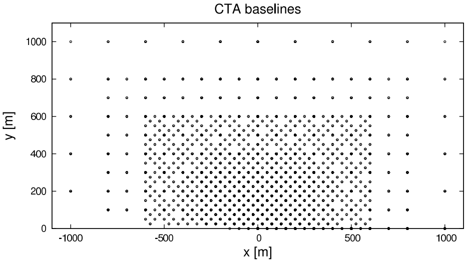


The Cherenkov Telescope Array (CTA)

- ACTs are ideal SII receivers.
- Easily adapted for optical SII ($\lambda \sim 400\,\mathrm{nm}$)
- Future arrays will provide thousands of simultanous baselines.
- SII working group in CTA.

Array design and (u, v) coverage



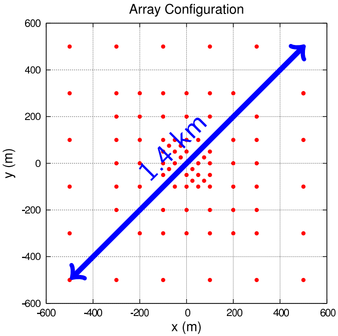


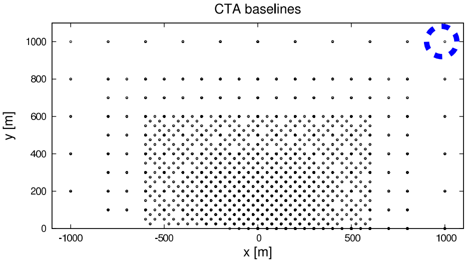
$\lambda = 400\,\mathrm{nm}$

$\Delta\theta_{min} \sim \frac{\lambda}{\Delta x_{max}} \sim 0.01\ mas$

$\Delta\theta_{max} \sim \frac{\lambda}{\Delta x_{min}} \sim 1\ mas$

Array design and (u, v) coverage





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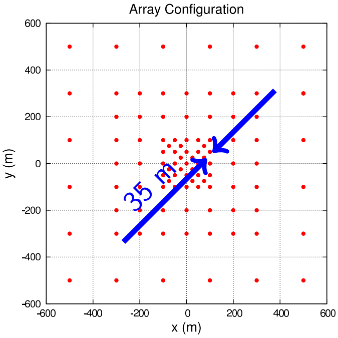

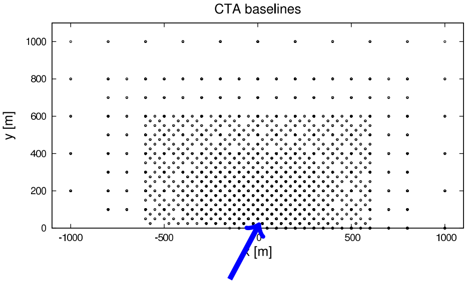

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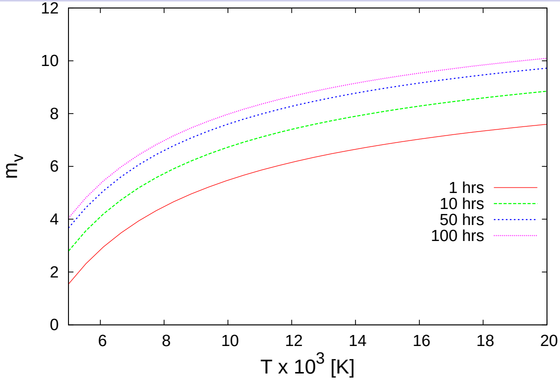
Array sensitivity at $\lambda = 400\ nm$

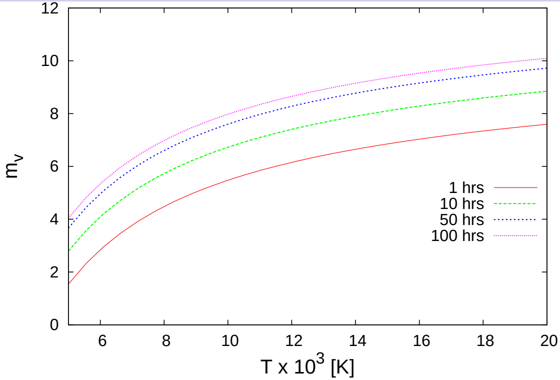


$$\boxed{SNR = n(\lambda, T, m_v)\, A\, \alpha\, |\gamma|^2 \sqrt{\Delta f t/2}}$$

$\sim$ 2500 detectable stars within 10 *hrs* (33000 in JMMC catalog).
Limiting magnitude of $\sim$ 9.6

(Nuñez et. al. 2012)

Array sensitivity at $\lambda = 400\ nm$



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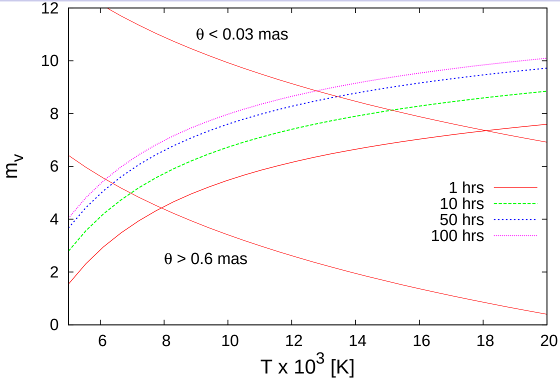

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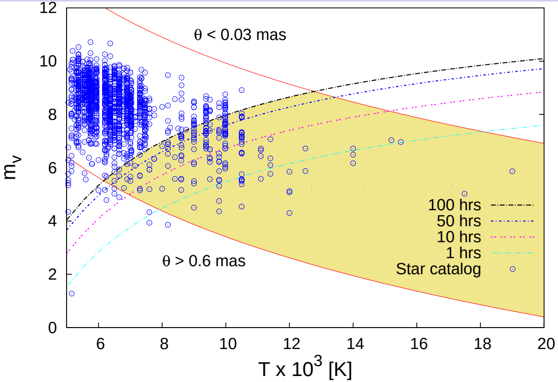

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(Nuñez et. al. 2012)

The imaging problem

The Fourier phase is not available from two-point intensity correlation measurements. Phase can be retrieved by:

- Theory of analytic functions: Cauchy-Riemmann equations
  (Holmes & Belenkii 2004, Nuñez et. al 2012a)

  The Fourier transform of an object of finite size (e.g. a star) is an analytic function.

- Gerchberg-Saxton algorithms
  (Fiennup 1981, Nuñez et al. 2012b, Strekalov this workshop)

  Iterative method that enforces constraints in Fourier and Image domains.

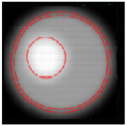
- Three-point correlations

  (Gamo 1963, Malvimat et al. 2013, Wentz & Saha this workshop)

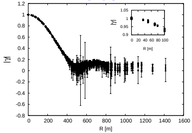
$$\frac{\langle I_i I_j I_k \rangle}{\langle I_i \rangle \langle I_j \rangle \langle I_k \rangle} = 1 + |\gamma_{ij}|^2 + |\gamma_{jk}|^2 + |\gamma_{ki}|^2 + 2Re\left[\gamma_{ij}\gamma_{jk}\gamma_{ki}\right] \qquad (1)$$

Simulation/Analysis overview (two-point correlations only)

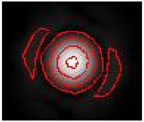
Pristine

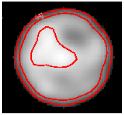


Data

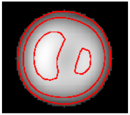


Hermite fit

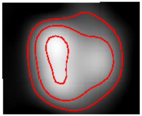




MiRA



Gerchberg-Saxton



Cauchy-Riemann

$$\arg\min\left\{\chi^2\right\}$$

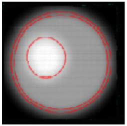
Thiebaut 2006

$$\begin{tikzcd}
\mathcal{O}_k \arrow[r, "\mathcal{F}(\mathcal{O}_k)"] & \tilde{\mathcal{O}}_k = \mathcal{M}_k e^{i\phi_k} \arrow[d, "\mathcal{M}_k = |\gamma|"] \\
\mathcal{O}_{k'} \arrow[u, "Mask"] & \tilde{\mathcal{O}}_k = |\gamma| e^{i\phi_k} \arrow[l, "\mathcal{F}^{-1}(\tilde{\mathcal{O}}_k)"']
\end{tikzcd}$$

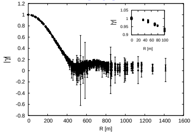
$$\frac{\partial \Phi}{\partial \psi} = \frac{\partial \ln R}{\partial \xi}$$
$$\frac{\partial \Phi}{\partial \xi} = -\frac{\partial \ln R}{\partial \psi}$$

Simulation/Analysis overview (Nuñez et al. 2012)

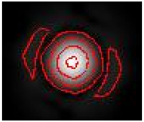
Pristine

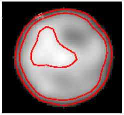


Data



Hermite fit





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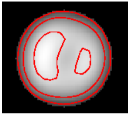
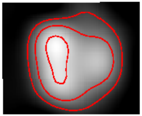


Gerchberg-Saxton



Cauchy-Riemann

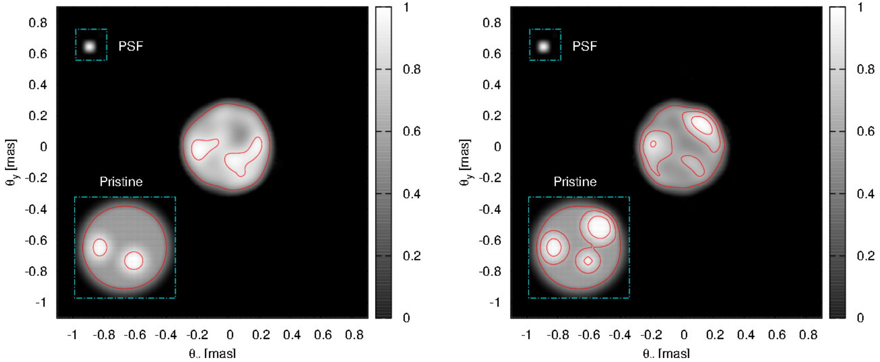
arg min $\{\chi^2\}$

Thiebaut 2006

$$\begin{tikzcd} \mathcal{O}_k \arrow[r, "\mathcal{F}(\mathcal{O}_k)"] & \tilde{\mathcal{O}}_k = \mathcal{M}_k e^{i\phi_k} \arrow[d, "\mathcal{M}_k = |\gamma|"] \\ \mathcal{O}_{k'} \arrow[u, "Mask"] & \tilde{\mathcal{O}}_k = |\gamma| e^{i\phi_k} \arrow[l, "\mathcal{F}^{-1}(\tilde{\mathcal{O}}_k)"'] \end{tikzcd}$$

$$\frac{\partial \Phi}{\partial \psi} = \frac{\partial \, lnR}{\partial \xi}$$
$$\frac{\partial \Phi}{\partial \xi} = -\frac{\partial \, lnR}{\partial \psi}$$

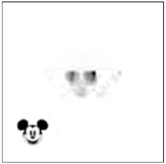
Post-processing example: Star spots



$\mathrm{m}_V = 3$, 10 *hrs* of observation

$\Delta T = 500°\mathrm{K}$

Nuñez et al. 2012, MNRAS



Hot Be stars

Observational signatures:

- H_α emission
- IR excess
- Broad, Double peaked or asymetric spectral lines
- Intrinsic polarization

Imply:

- Dense gaseous circumstellar environment
- Fast rotating $\Rightarrow$ Pole Brightening (von Zeipel)
- Disk

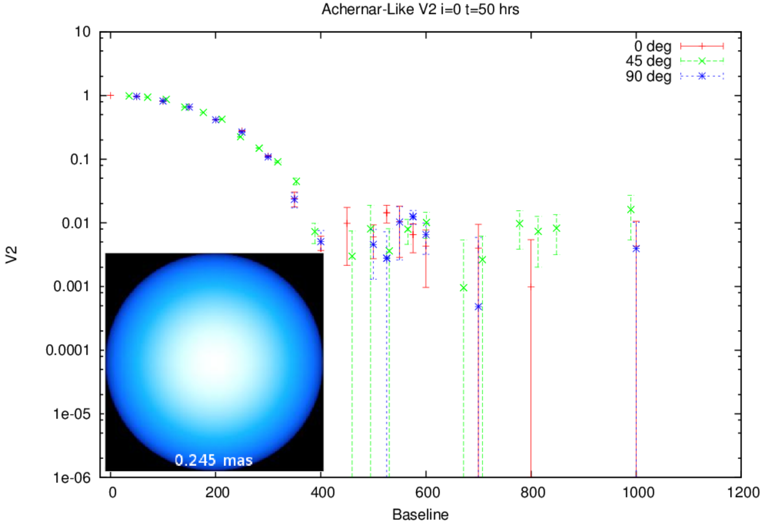
With Intensity Interferometry we could:

- Measure angular diameters (for different baseline orientation)
- Map brightness distribution
- Measure correlations as a function of time delay $\Rightarrow$ Spectrum

Modeling benefits from imaging

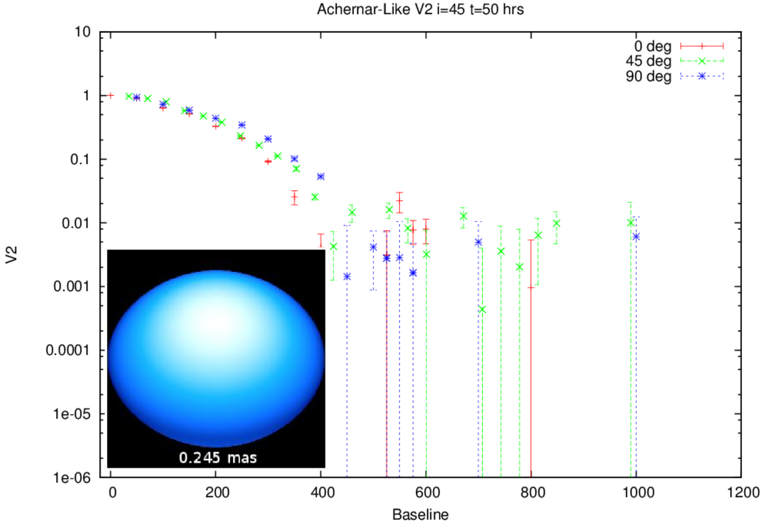
Simulated Example: Fast Rotating Be stars

Work in progress with A. Domiciano de Souza. CTA sim. ($m_v = 4$)



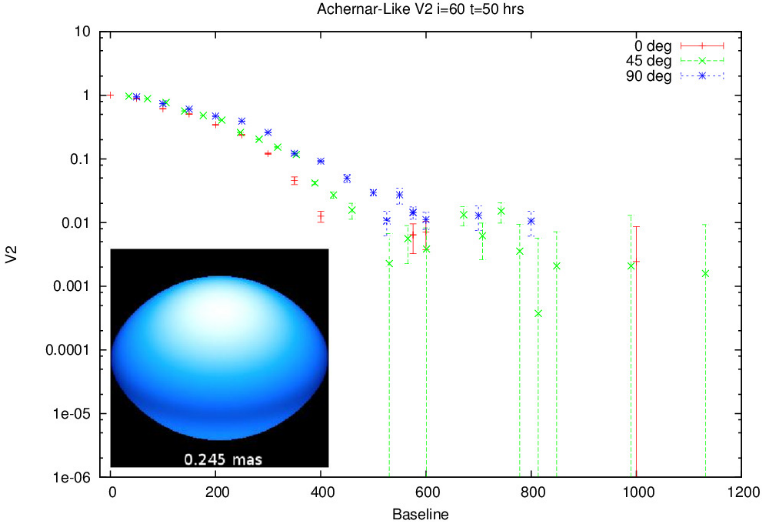
Simulated Example: Fast Rotating Be stars

Work in progress with A. Domiciano de Souza. CTA sim. $(m_v = 4)$



Simulated Example: Fast Rotating Be stars

Work in progress with A. Domiciano de Souza. CTA sim. $(m_v = 4)$



Simulated Example: Fast Rotating Be stars

Work in progress with A. Domiciano de Souza. CTA sim. ($m_v = 4$)

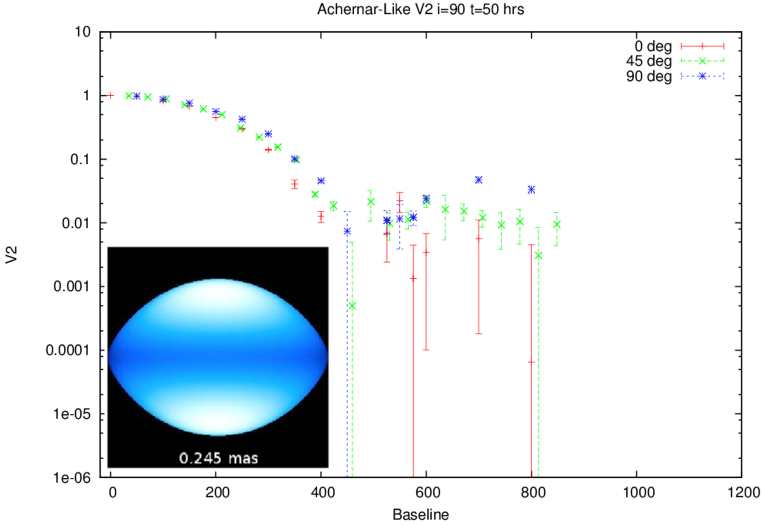
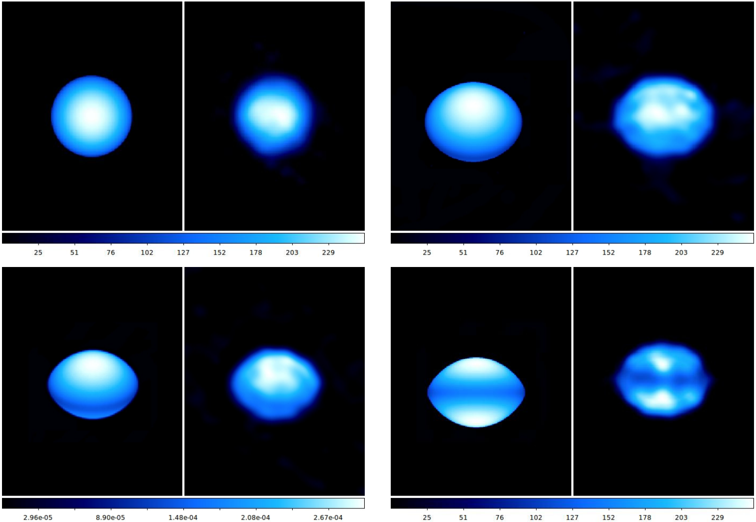


Image reconstruction of Be stars using MiRA

Using two- and **three-point** correlation data



Final Remarks

- Intensity Interferometry can significantly increase the angular resolution: $\Delta\theta \sim 0.01\, mas$ (with coarse optics!)
- The cost is lower sensitivity ($m_v < 10,\ T_{obs} \sim 10 hrs$)
- Imaging is restricted to brighter stars ($m_v < 6$)
- Three-point correlations improve imaging capabilities
- Fast-rotating Be stars are ideal targets for CTA used for SII $\sim$ 70 B-type stars, $\sim$ 160 Fast rotators ($m_v < 5$)
- What about the time domain?
  (e.g. Spectro-Intensity-Interferometry)