More than just a phase: The LSST atmospheric PSF

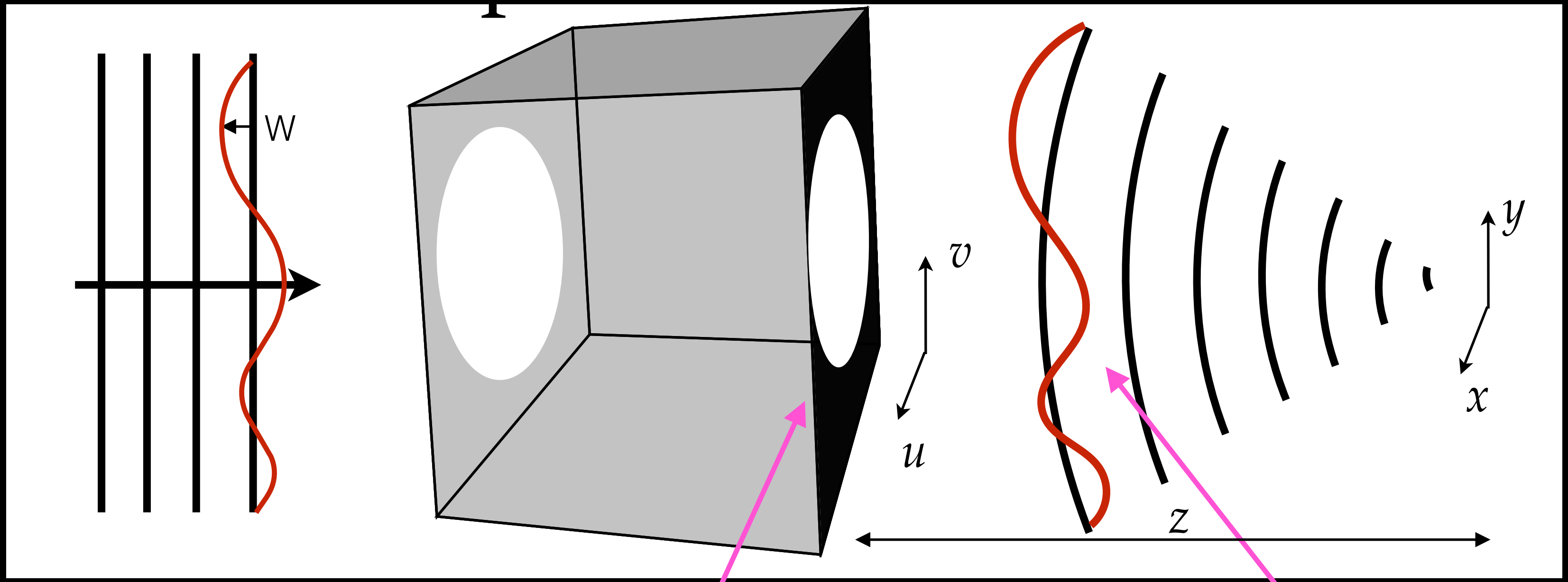
Josh Meyers

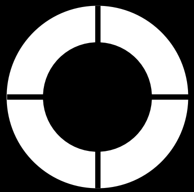
Warm up.

- Decide if each statement is true or false. If false, say why.
  - Telescopes turn angles into positions.
  - The PSF and wavefront contain the same information.
  - The PSF does not depend on the object being imaged.

Fourier Optics

credit: Aaron Roodman



$P(u, v)$  Aperture transmission function

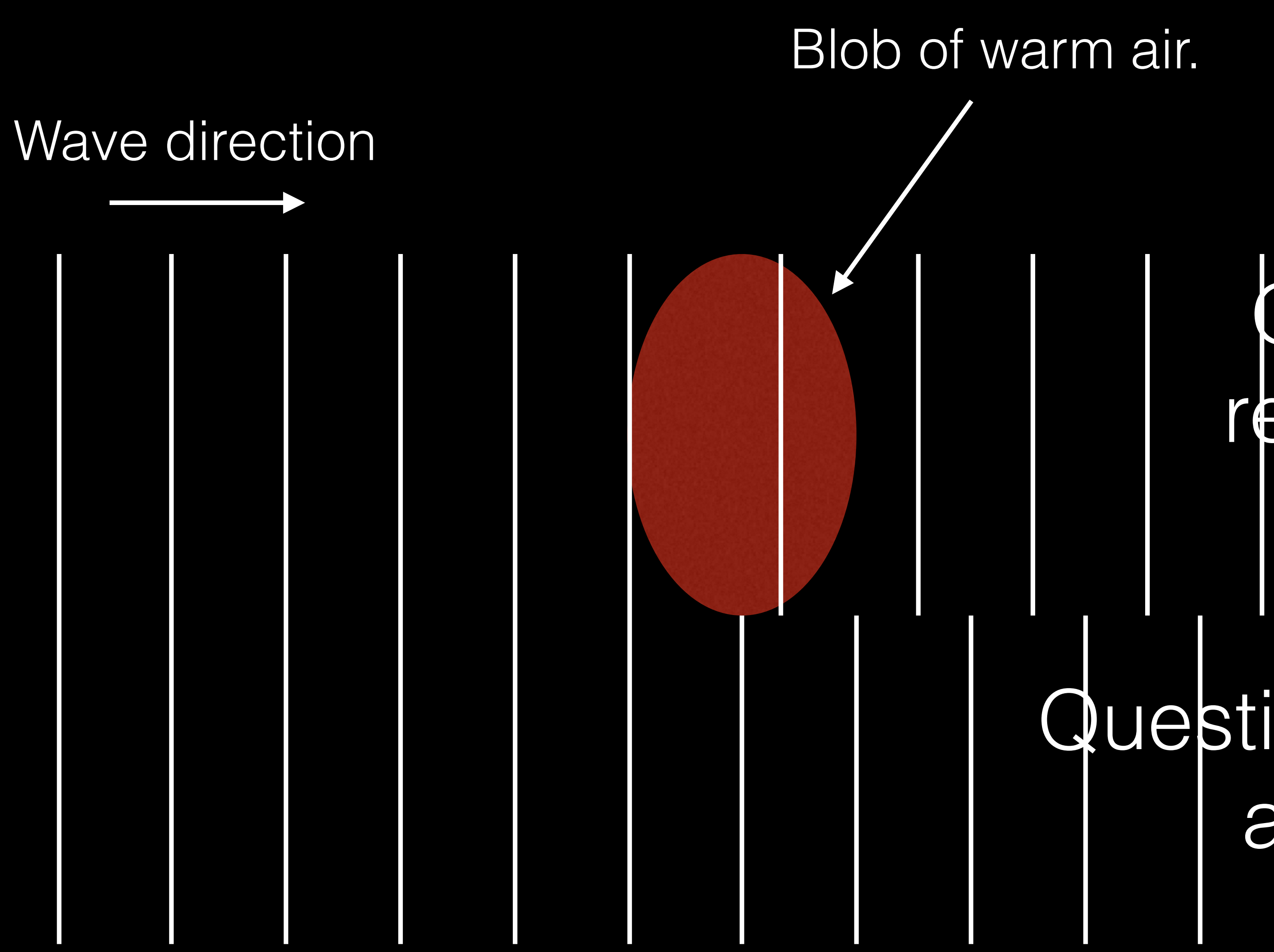
Wavefront aberrations

$$I(x,y) \propto \left| \int P(u,v) \exp\left[\frac{-2\pi i}{\lambda} W(u,v)\right] \exp\left[\frac{2\pi i}{\lambda z}(xu + yv)\right] \mathrm{d}u\, \mathrm{d}v \right|^2$$

Fourier transform kernel

Atmospheric Phase: refractive index of air

$$n = 1 + 0.00029\,\frac{\rho}{1.3\times10^{-3}\,\mathrm{g\,cm^{-3}}}$$



Question 1: Draw resulting wavefront

Question 2: Why temperature and not pressure?

Data!

- Chris Stubbs told me last December that I need more real data, less simulations…
- Happens that I'm on the time allocation committee for one telescope…

Sirius

115 mm aperture

24 frames per second

https://youtu.be/lqg9_gsgAIA

Why does the image change so rapidly?

Atmosphere, vibrations, tracking errors, noise, scintillation.

Defocused

Sirius

115 mm aperture

24 frames per second

~1cm out-of-focus

https://youtu.be/izpvb25s68w

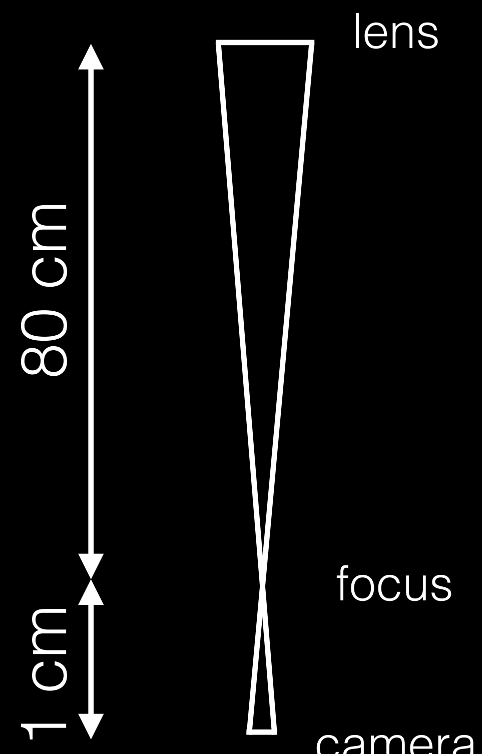
Question: Is the ~1 cm out-of-focus image more like the focal plane or the pupil plane?

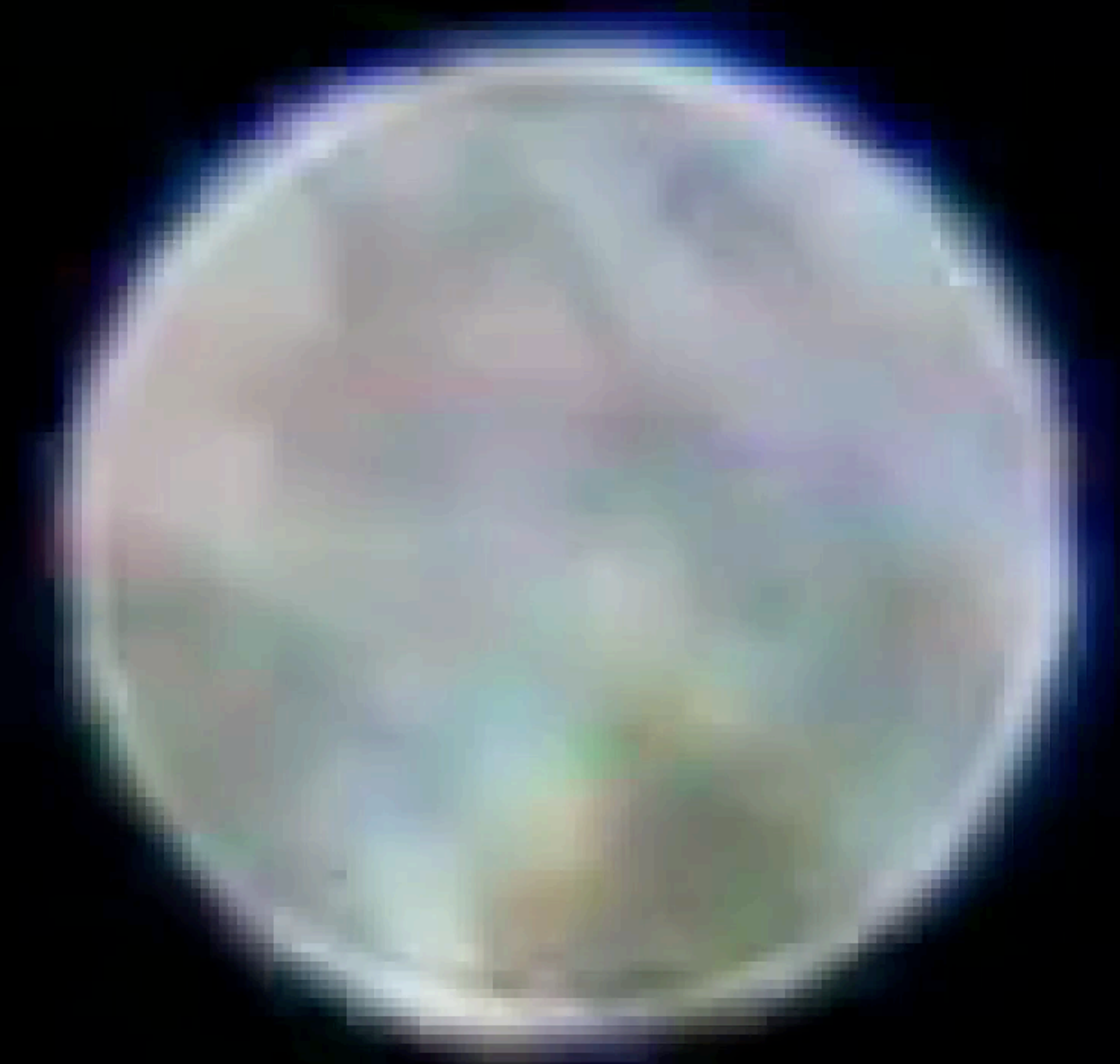
Sirius

115 mm aperture

24 frames per second

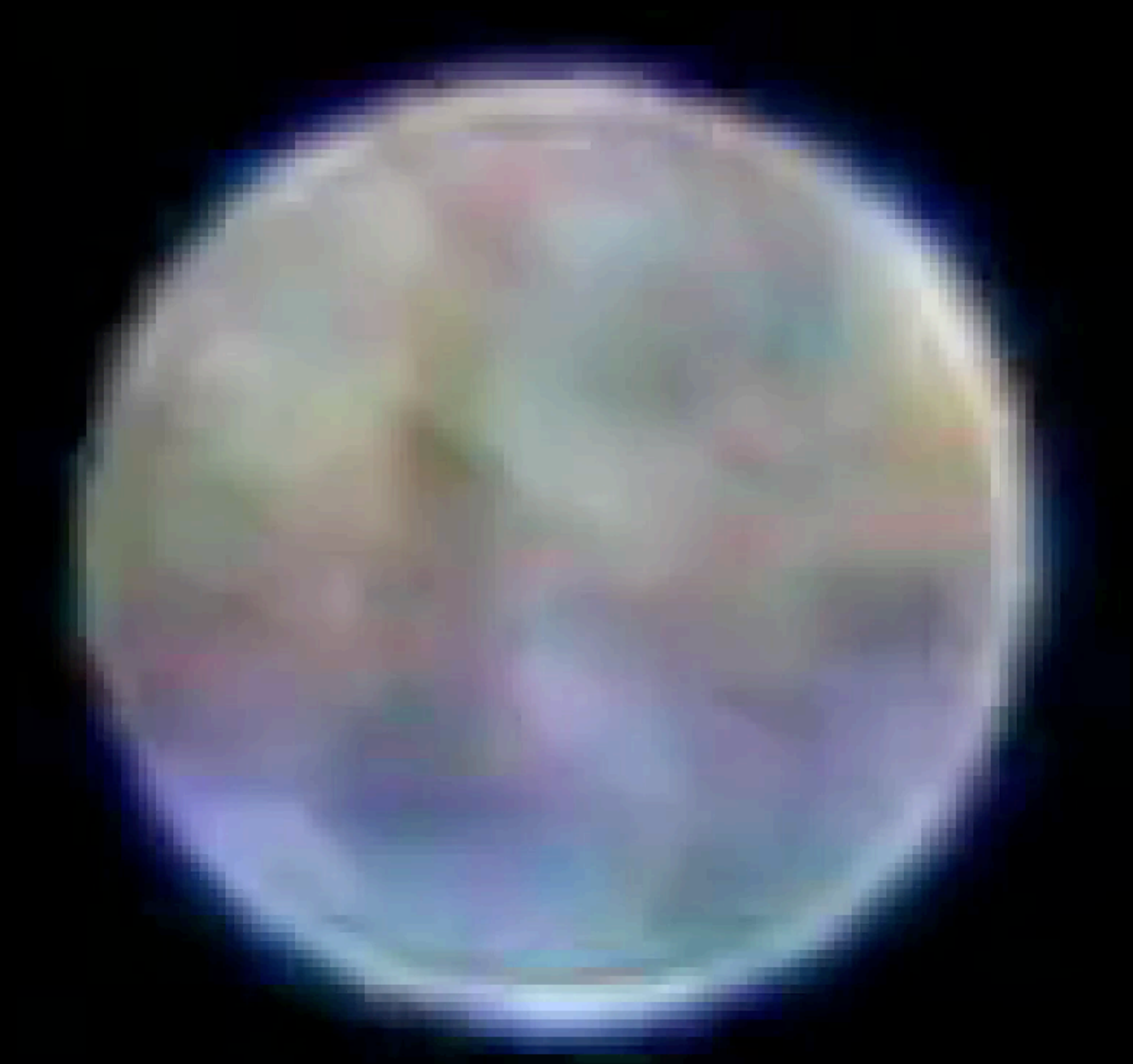
~1cm out-of-focus





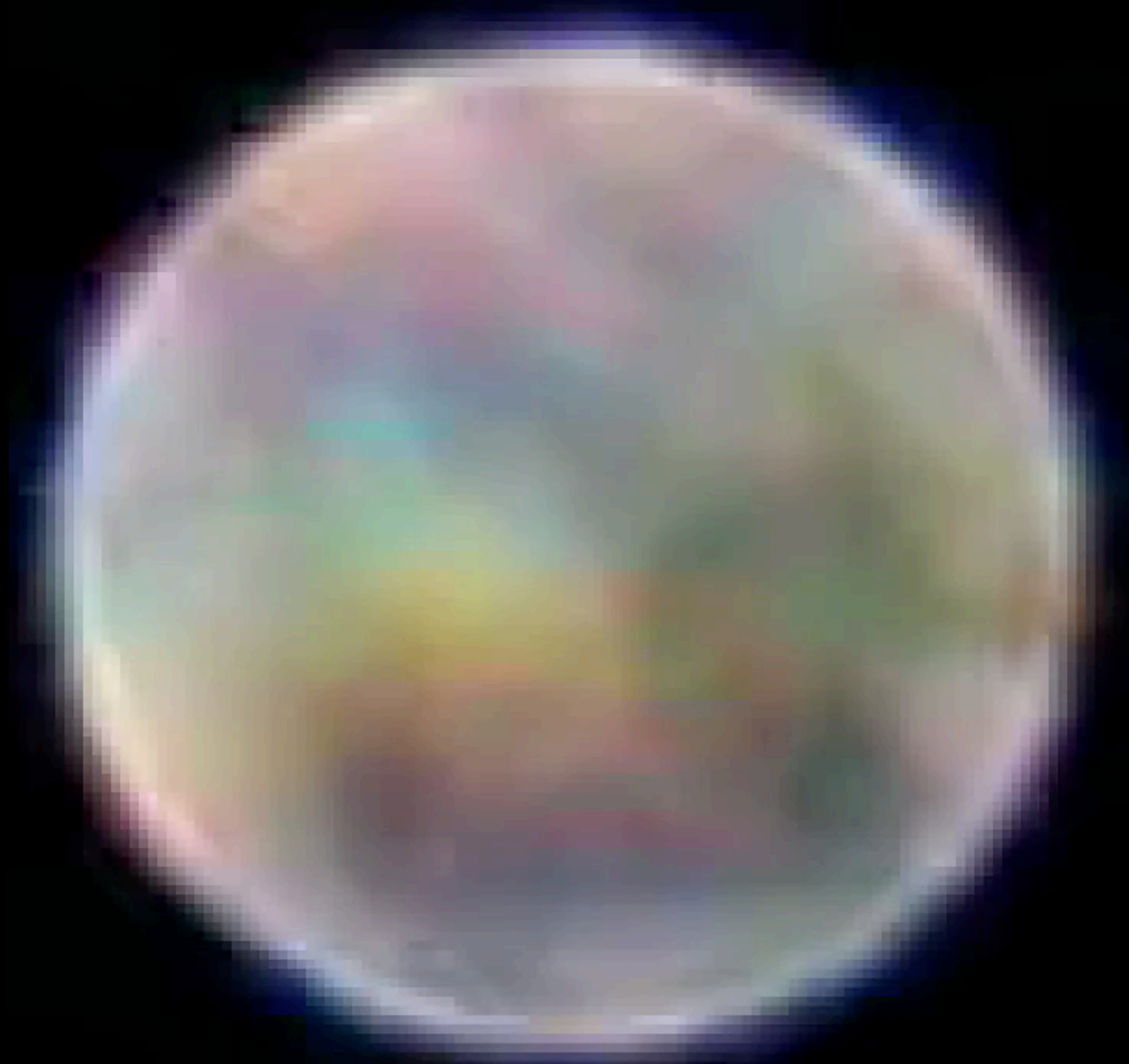
https://youtu.be/pd5cdJiuYeI

More fun with out-of-focus Sirius



https://youtu.be/Xlw1l2h3Dv4

More fun with out-of-focus Sirius



https://youtu.be/P_Z0lRWj6jA

In focus with the heat gun.

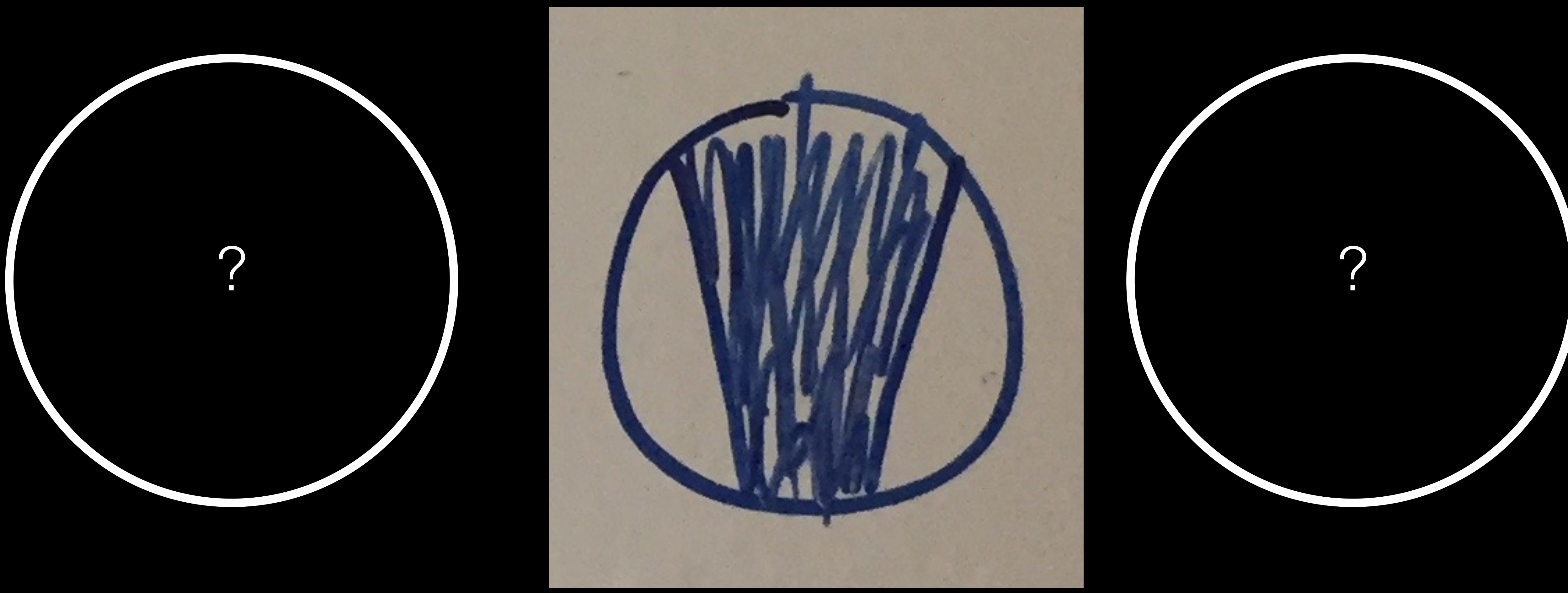
https://youtu.be/7SiGQK7JiCc

Higher spatial frequencies in wavefront

=

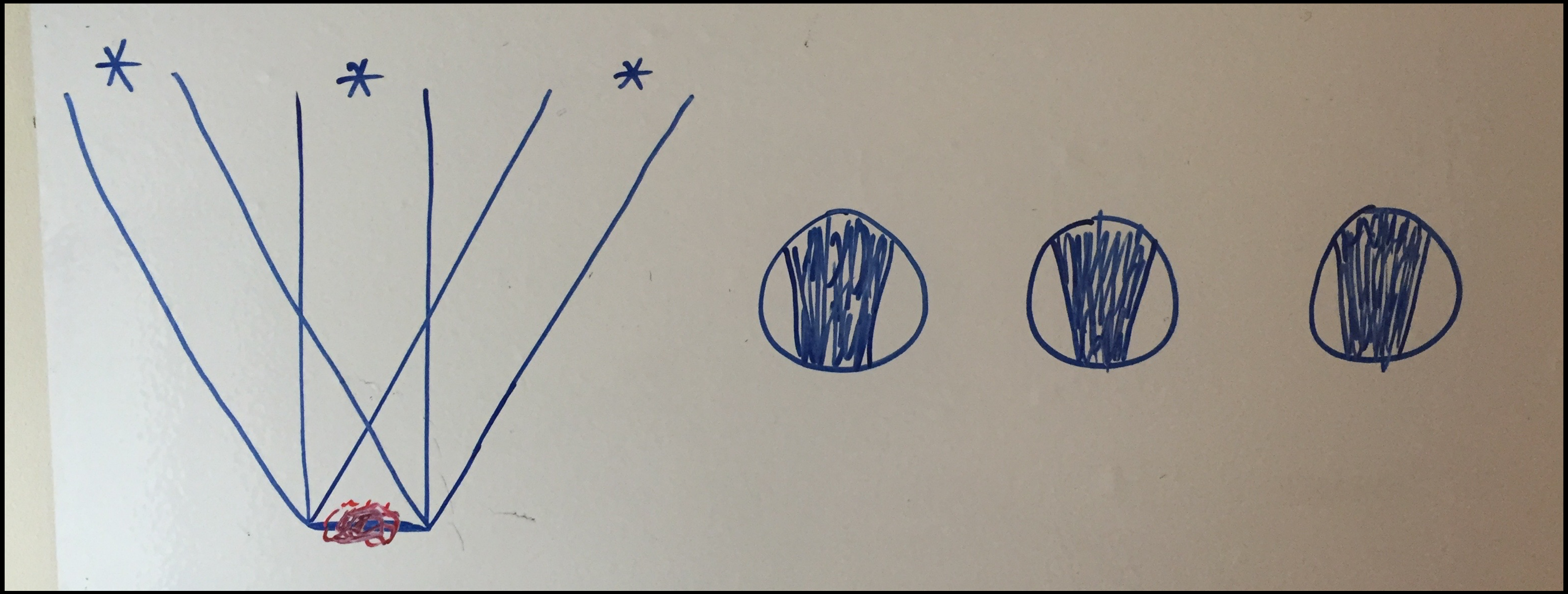
Larger PSF

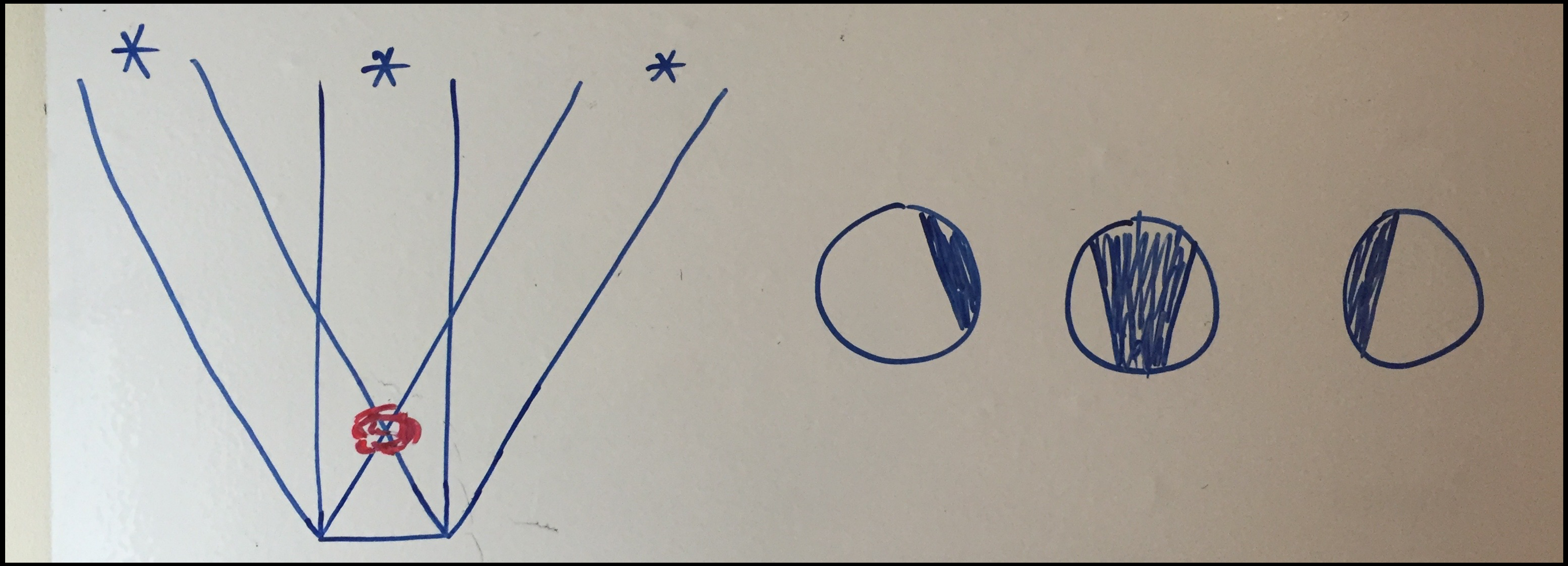
Problem: Describe (draw) the out-of-focus images for multiple stars in the same field of view for the heat gun demo.



- Also, what would happen to the multiple star images if the heat gun was farther away from the telescope?

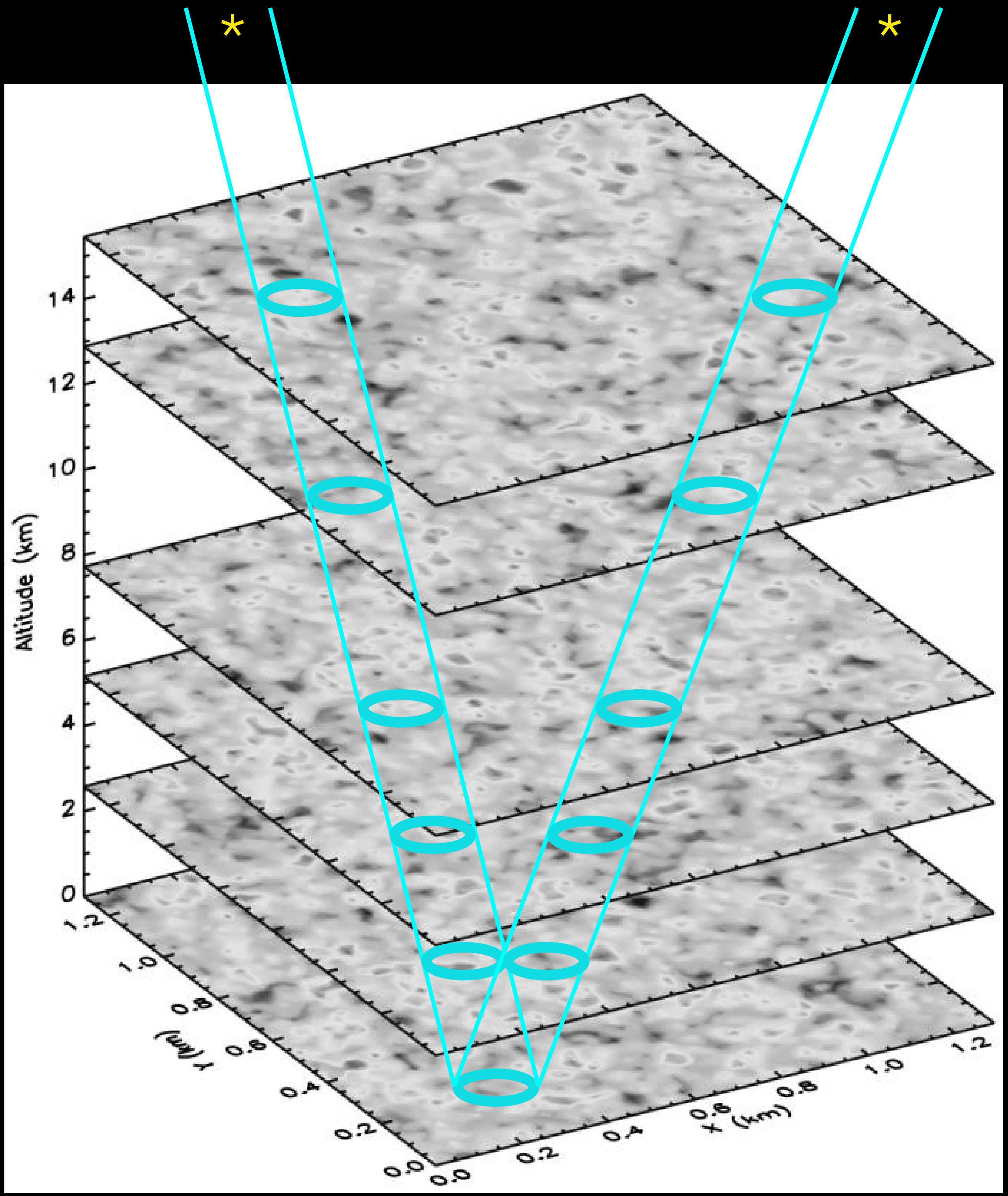
Question: Describe (draw) the wavefront for multiple stars in the same field of view for the heat gun example.





Simulation

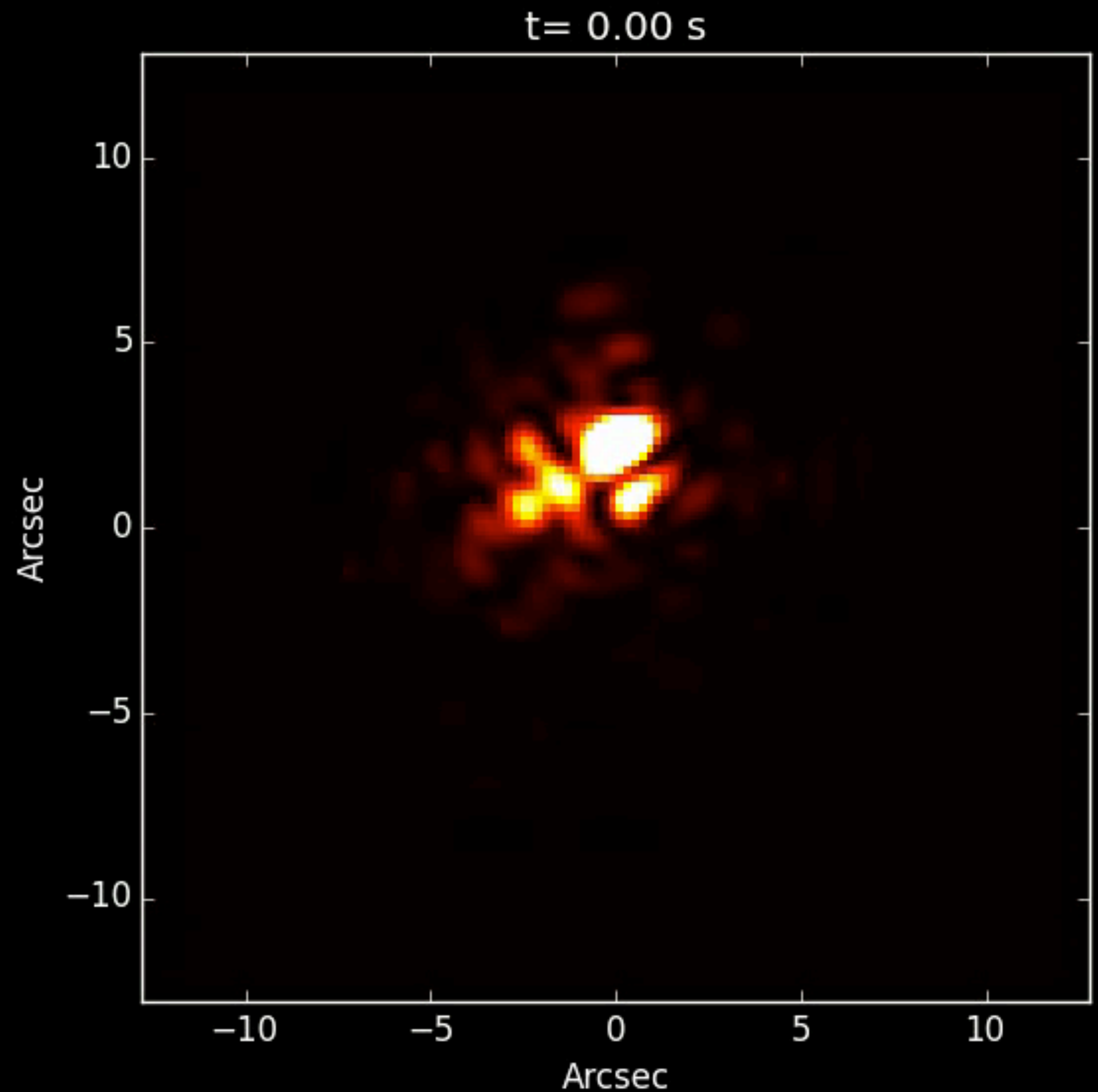
- Represent 3D atmosphere as a series of 2D layers.
- Project telescope aperture through these screens.
- Add turbulence from all screens together. Evaluate Fourier transform.
- Turbulence pattern may evolve and/or drift in the wind during exposure.



Jee+Tyson11

Aperture size

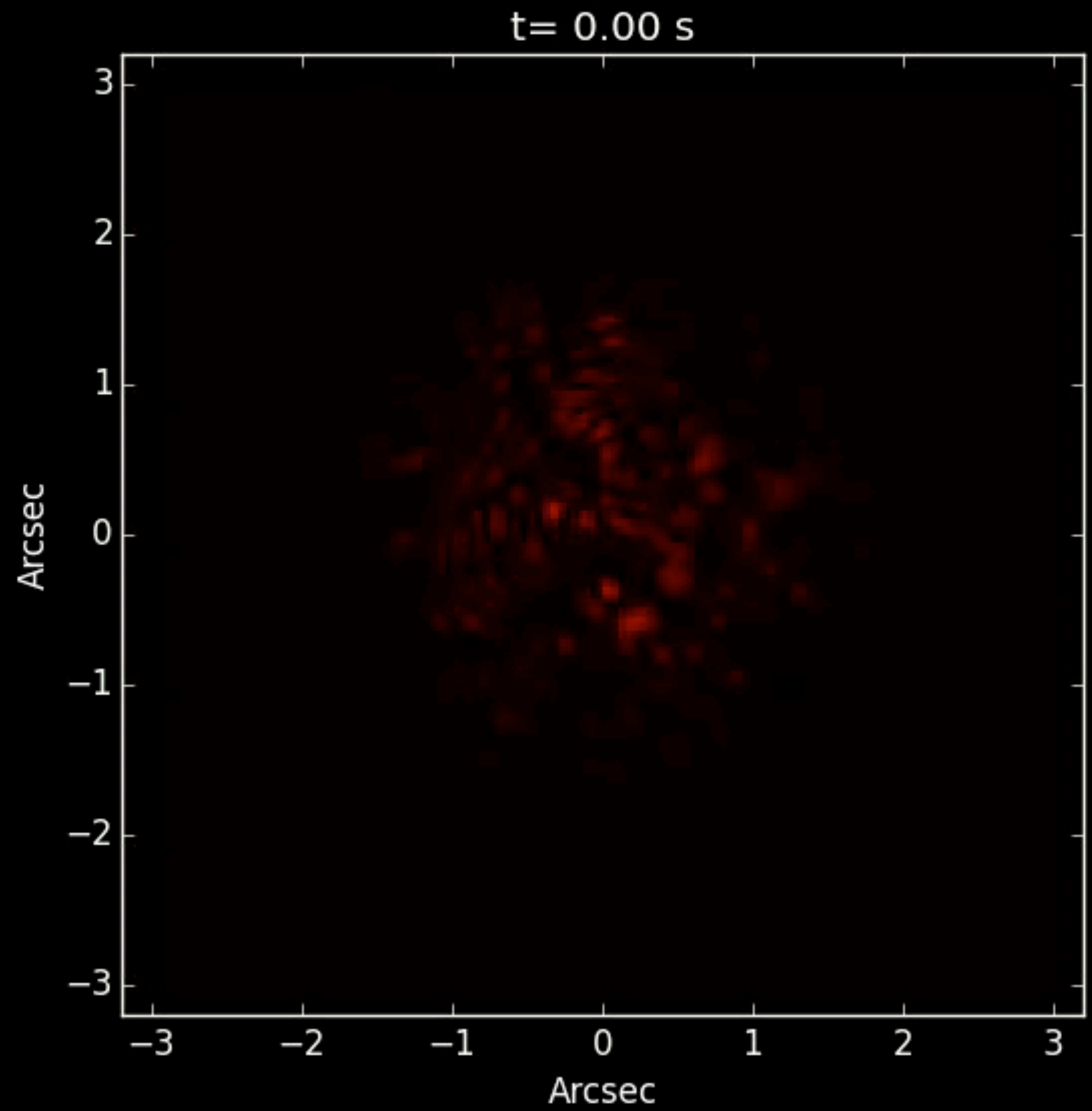
0.115 m aperture



https://youtu.be/y_aiCf4iSD8

Aperture size

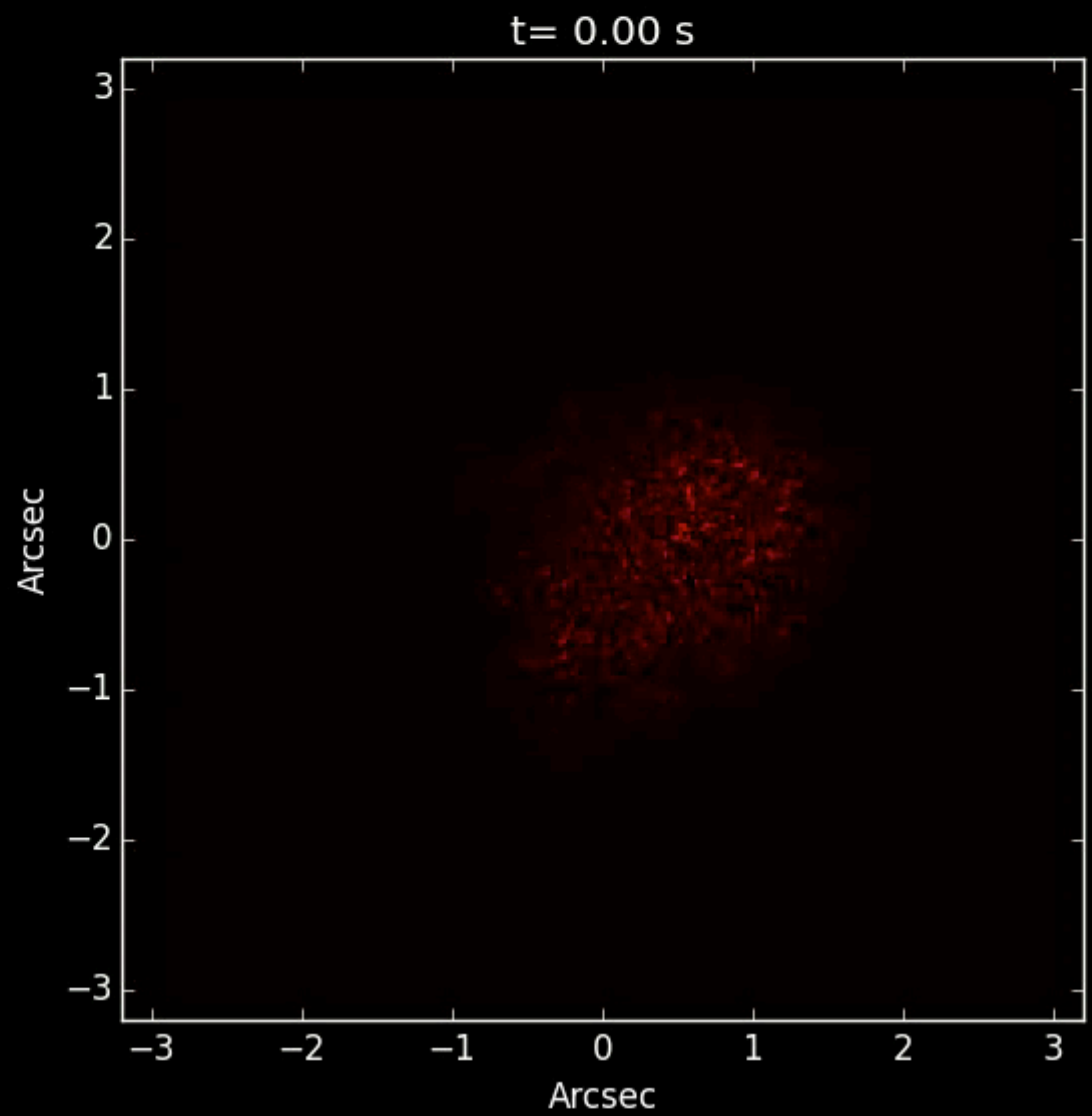
1 m aperture



https://youtu.be/hF707n6dDOw

Aperture size

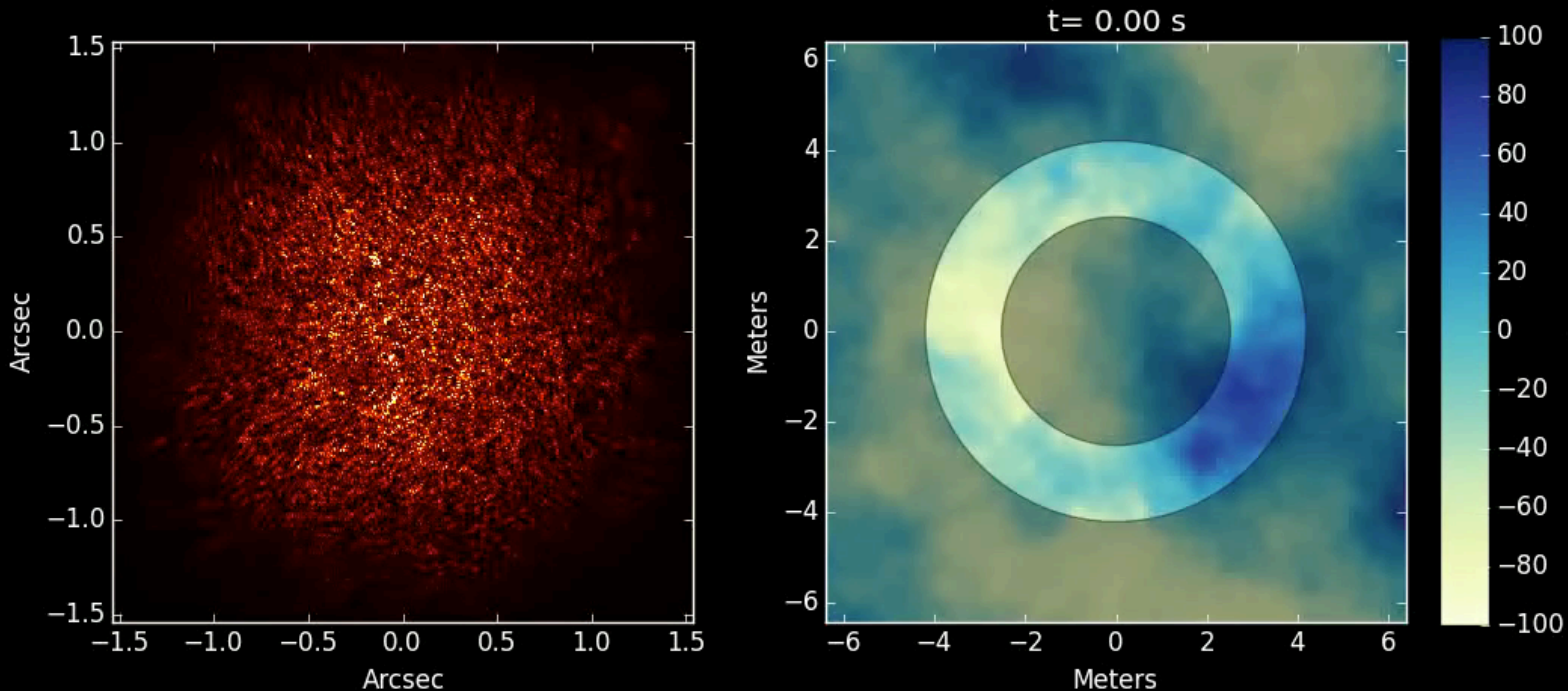
4 m aperture



https://youtu.be/nXTSZjjWszA

Question: Why do the speckles have the size that they have?

8.4 m aperture w/ obstruction

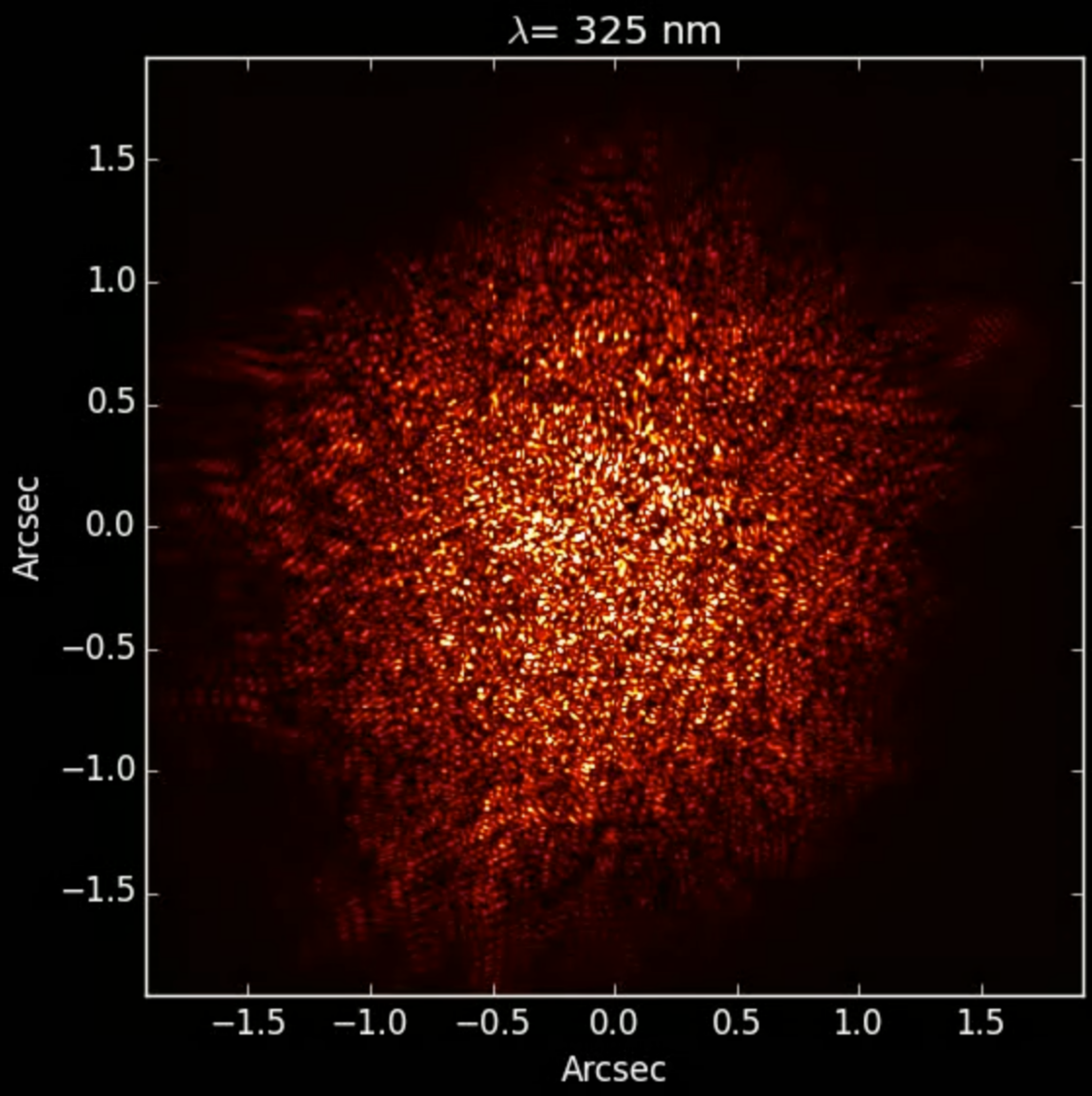


https://youtu.be/Sfj_px72mMA

Question: How does the PSF change with wavelength?

$$I(x,y) \propto \left| \int P(u,v) \exp\left[\frac{-2\pi i}{\lambda} W(u,v)\right] \exp\left[\frac{2\pi i}{\lambda z}(xu+yv)\right] \mathrm{d}u\,\mathrm{d}v \right|^2$$

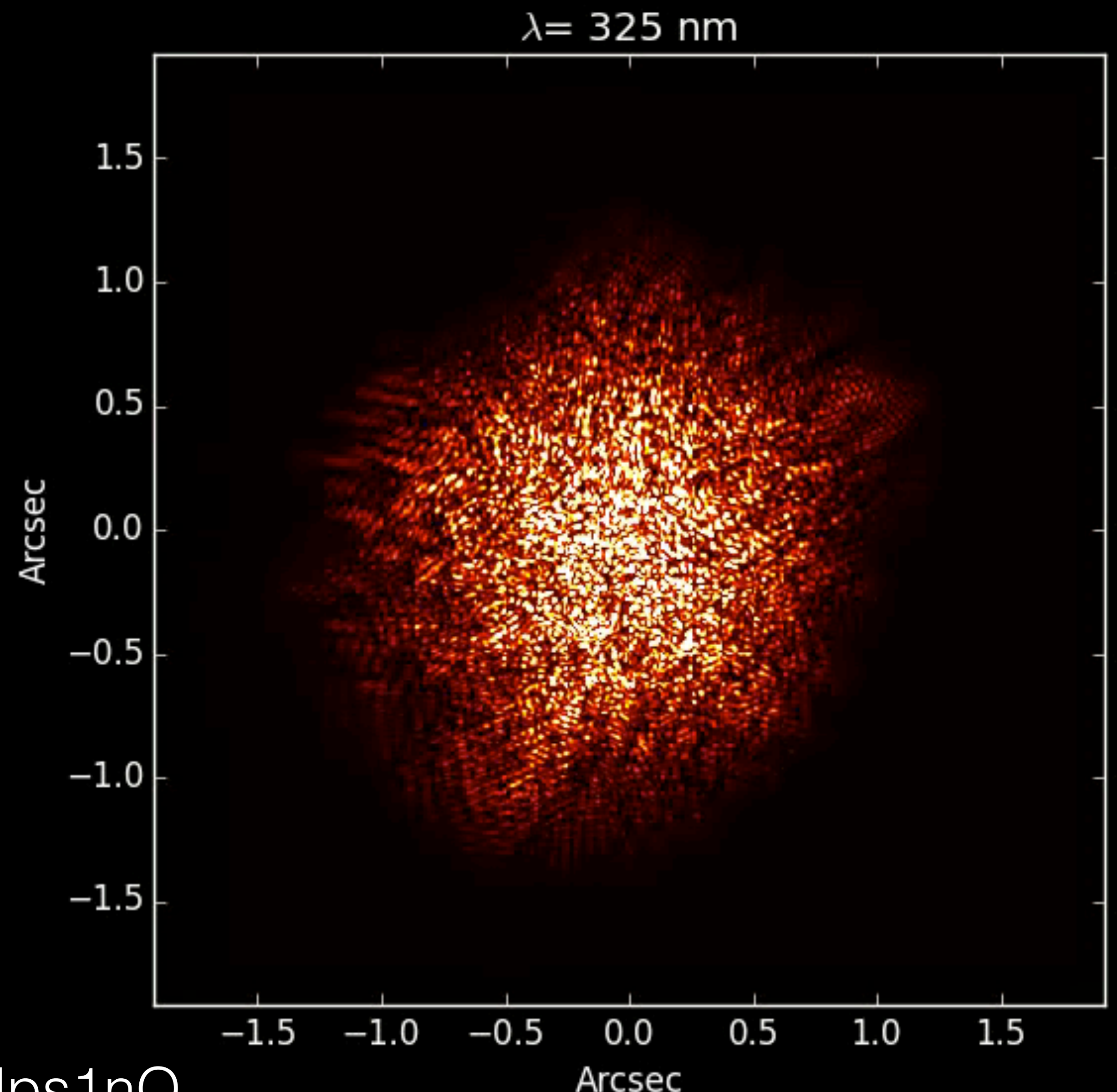
- Wavelength shows up twice.
  - Scales the wavefront
  - Part of Fourier transform kernel
- Take one part at a time.



Question: How does the PSF change with wavelength?

$$I(x,y) \propto \left| \int P(u,v) \exp\left[\frac{-2\pi i}{\boxed{500\,\mathrm{nm}}} W(u,v)\right] \exp\left[\frac{2\pi i}{\lambda z}(xu+yv)\right] \mathrm{d}u\,\mathrm{d}v \right|^2$$

Hold wavefront scaling constant



$$\left(\frac{x}{z}, \frac{y}{z}\right)$$

is Fourier conjugate with

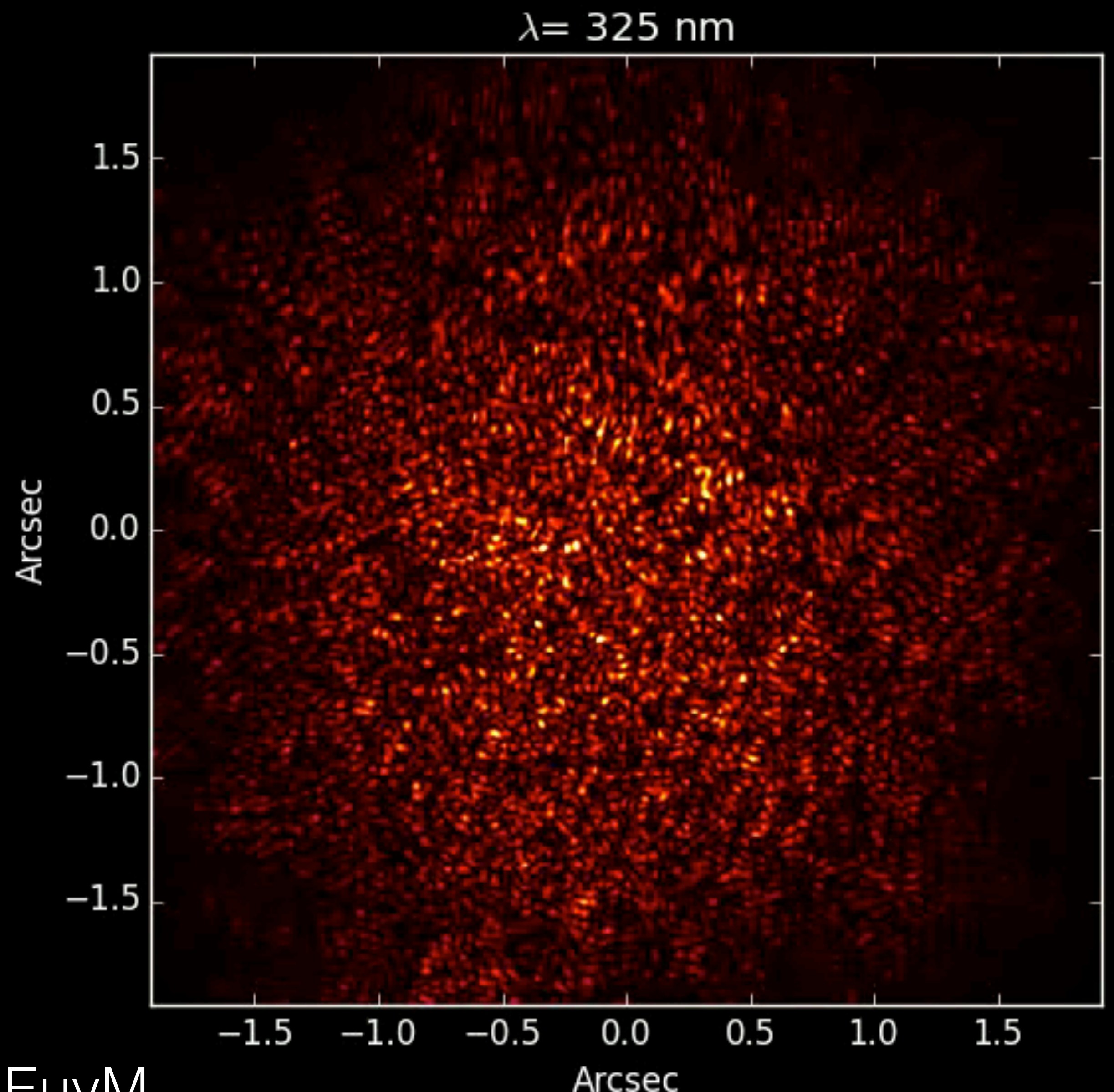
$$\left(\frac{u}{\lambda}, \frac{v}{\lambda}\right)$$

https://youtu.be/L83_gdps1nQ

Question: How does the PSF change with wavelength?

$$I(x,y) \propto \left| \int P(u,v) \exp\left[\frac{-2\pi i}{\lambda} W(u,v)\right] \exp\left[\frac{2\pi i}{\boxed{500\,\mathrm{nm}}\, z}(xu+yv)\right] \mathrm{d}u\, \mathrm{d}v \right|^2$$

Hold Fourier scaling constant



https://youtu.be/1vj1j0GEuyM

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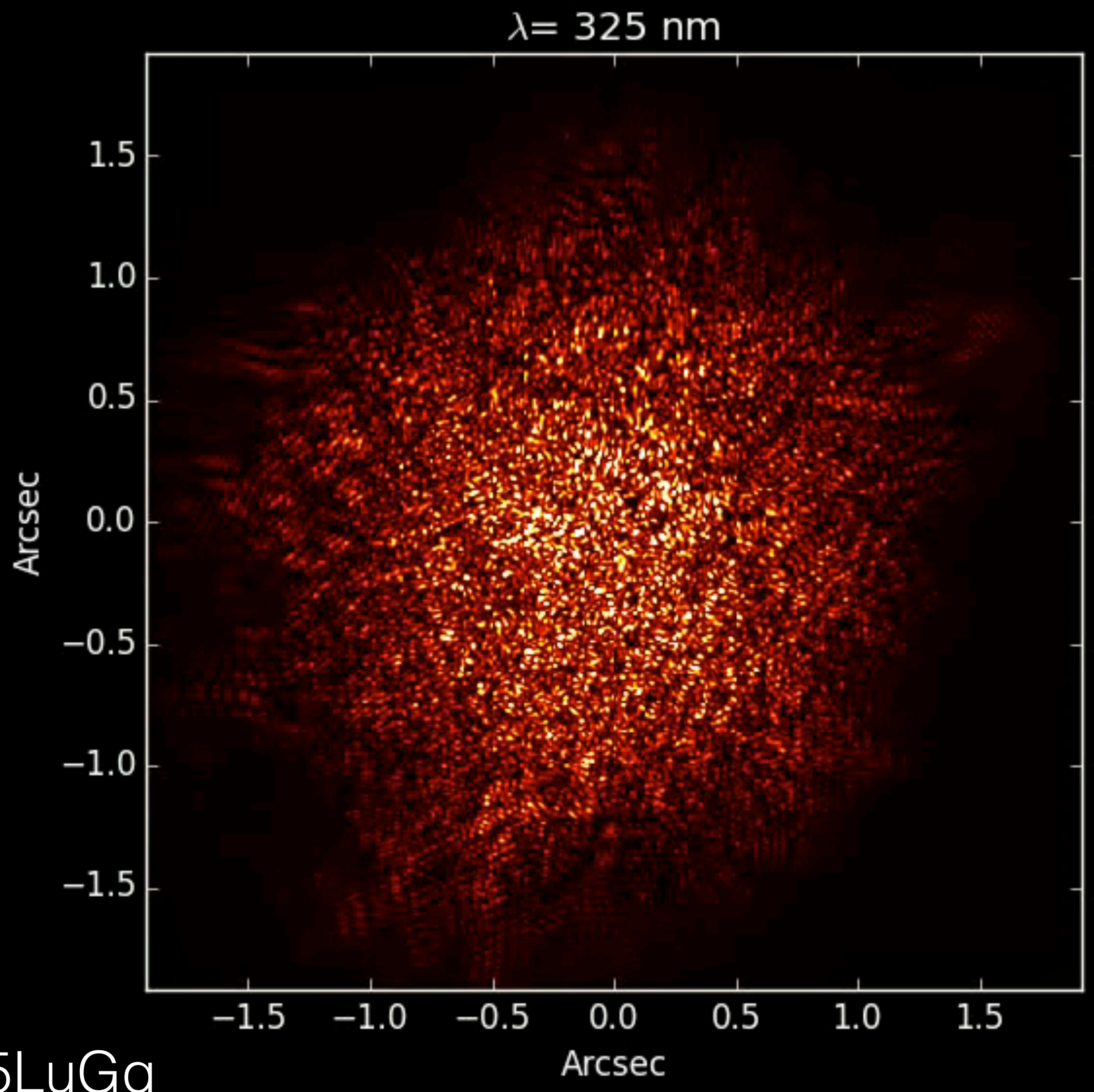
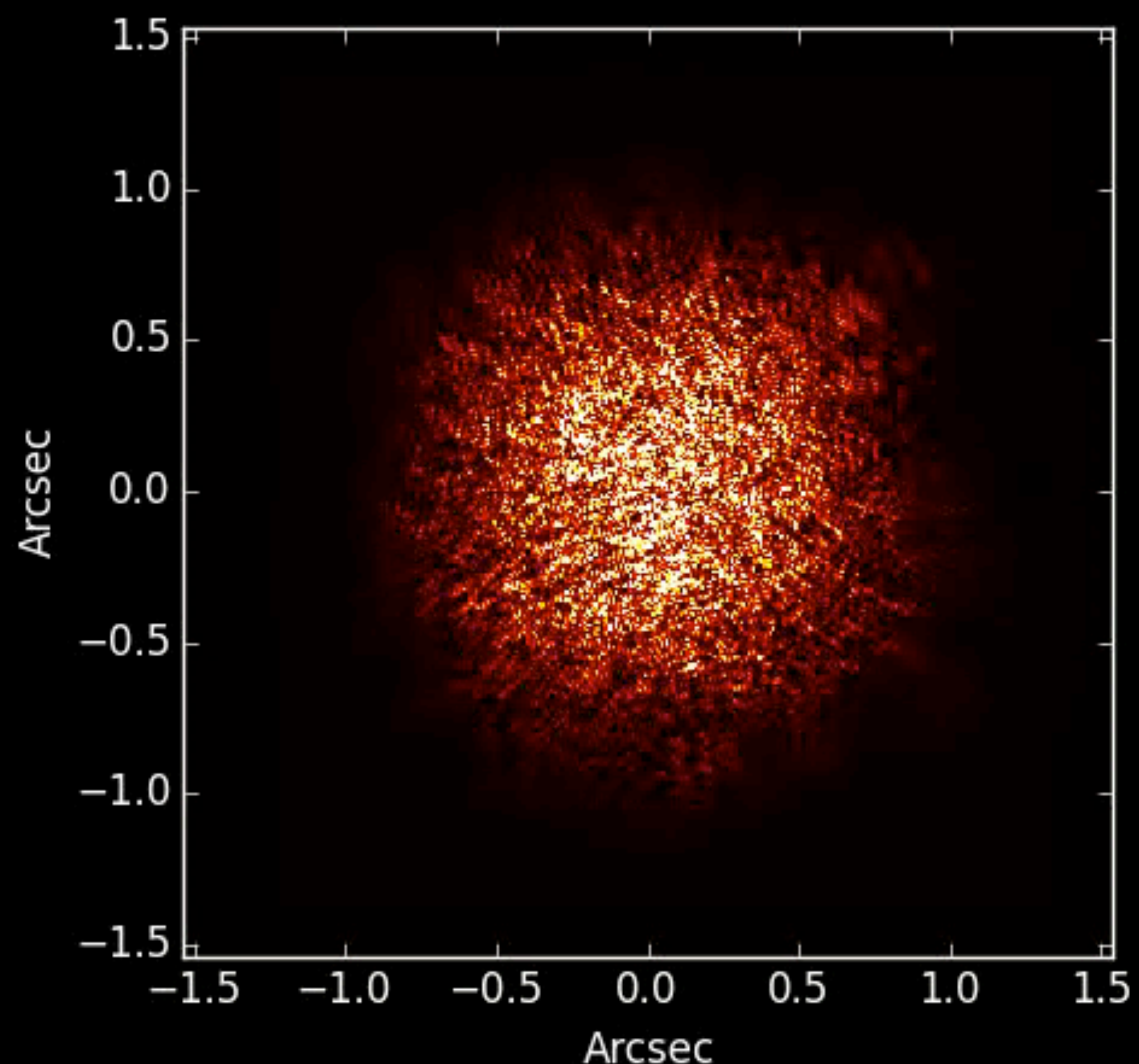
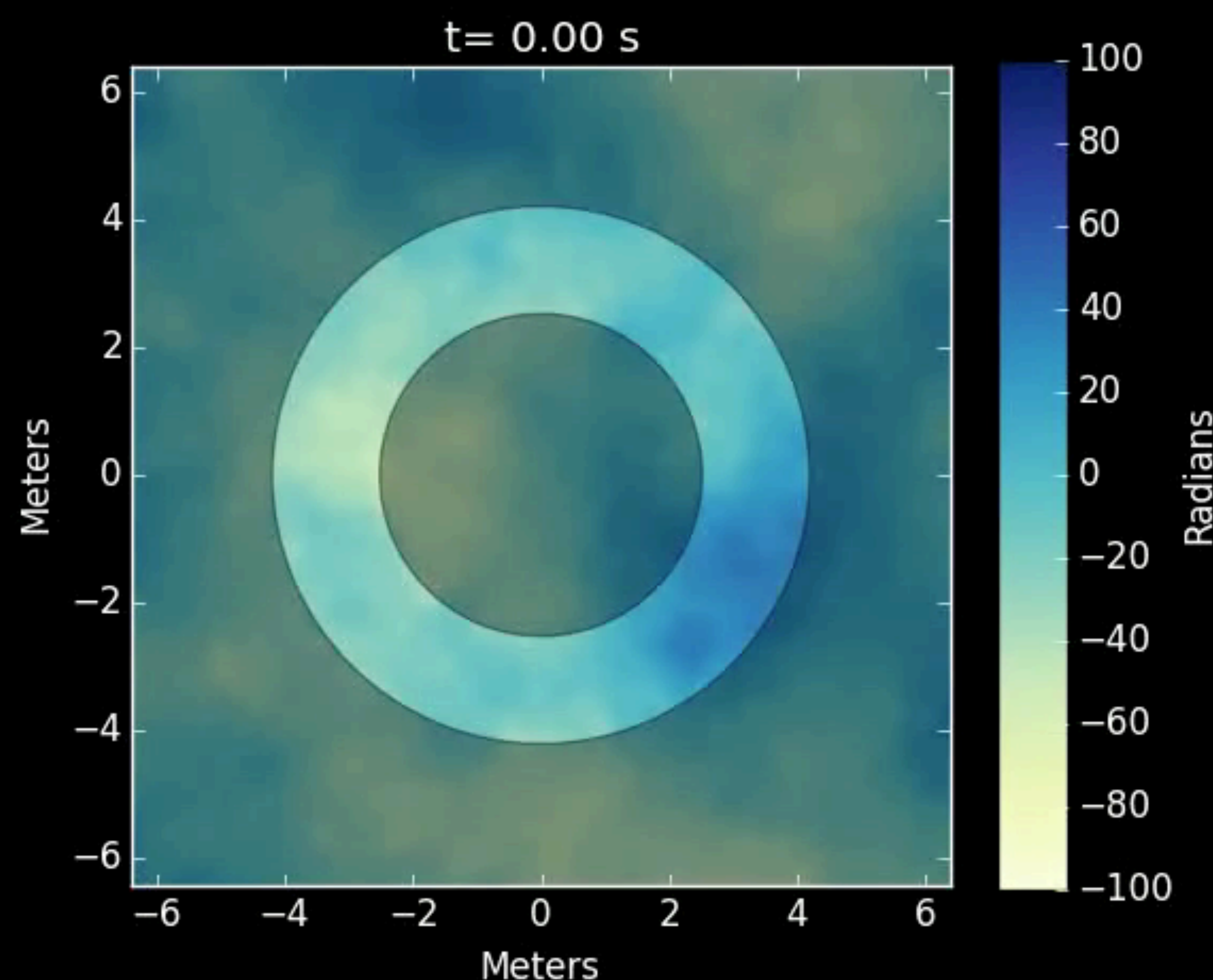


https://youtu.be/x3dTZk5LuGg

PSF variation in time and space.

- Wind blows “frozen” pattern of turbulence across the sky during an exposure.





PSF variation in time and space.

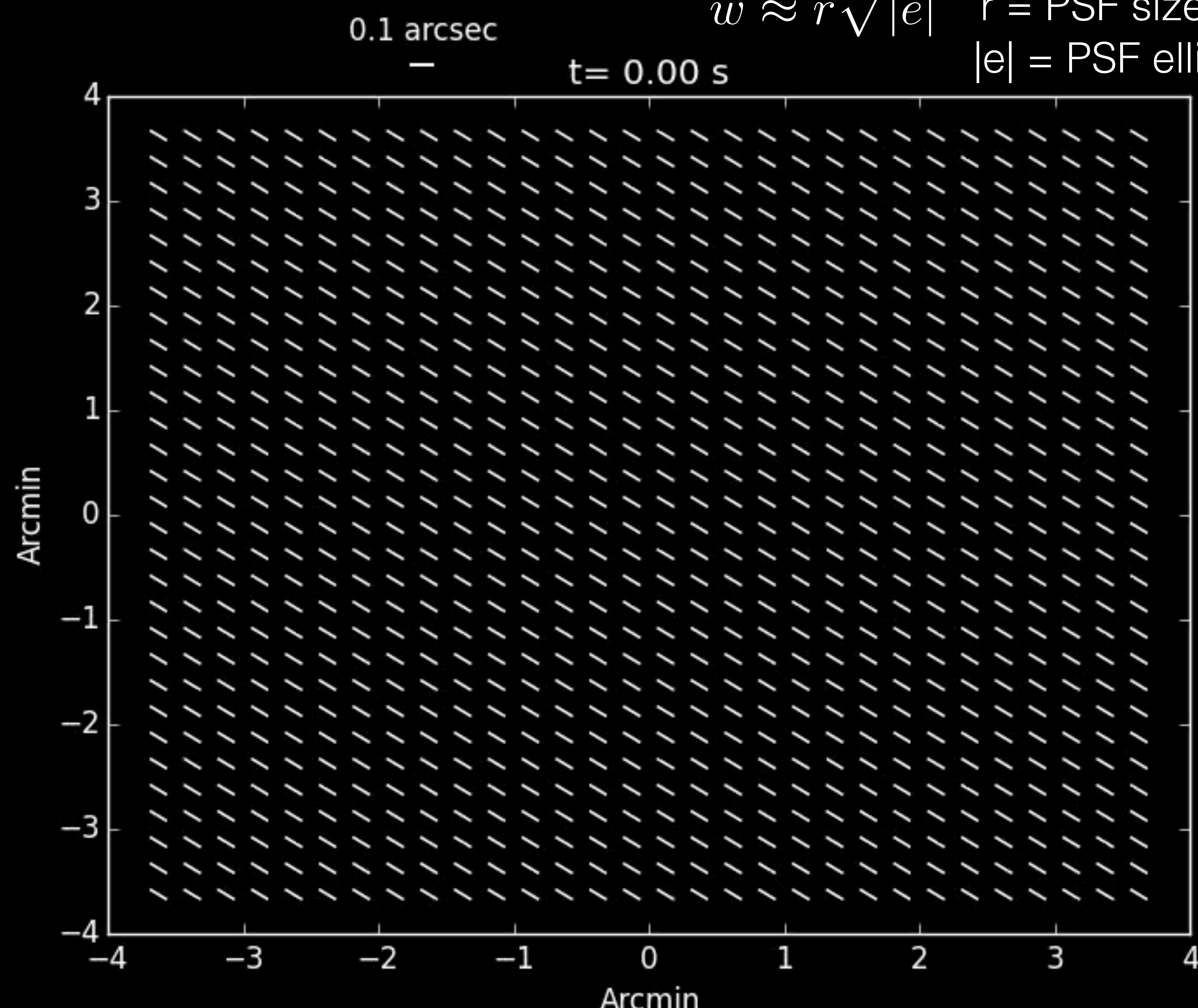
- Wind blows “frozen” pattern of turbulence across the sky during an exposure.
- Question: For a single turbulent layer blowing to the North, how does the PSF variation in time relate to the variation in space for the following layer altitude?
    - 0 km
    - 1 km
    - 3 km

PSF variation in time and space.

0 km

$w \approx r\sqrt{|e|}$ r = PSF size

|e| = PSF ellipticity magnitude



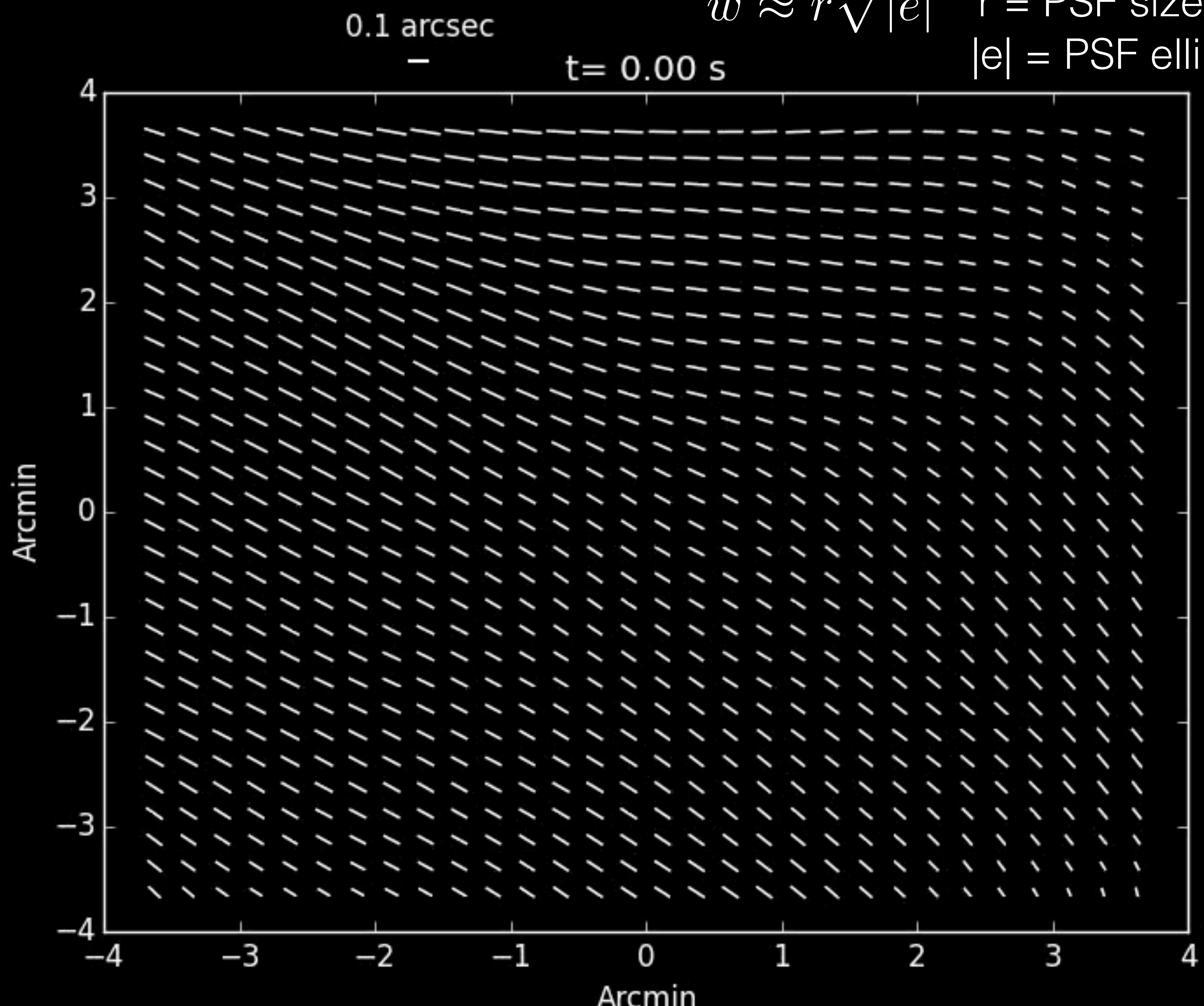
https://youtu.be/gmoYqFwcxcw

PSF variation in time and space.

1 km

$w \approx r\sqrt{|e|}$ r = PSF size

|e| = PSF ellipticity magnitude



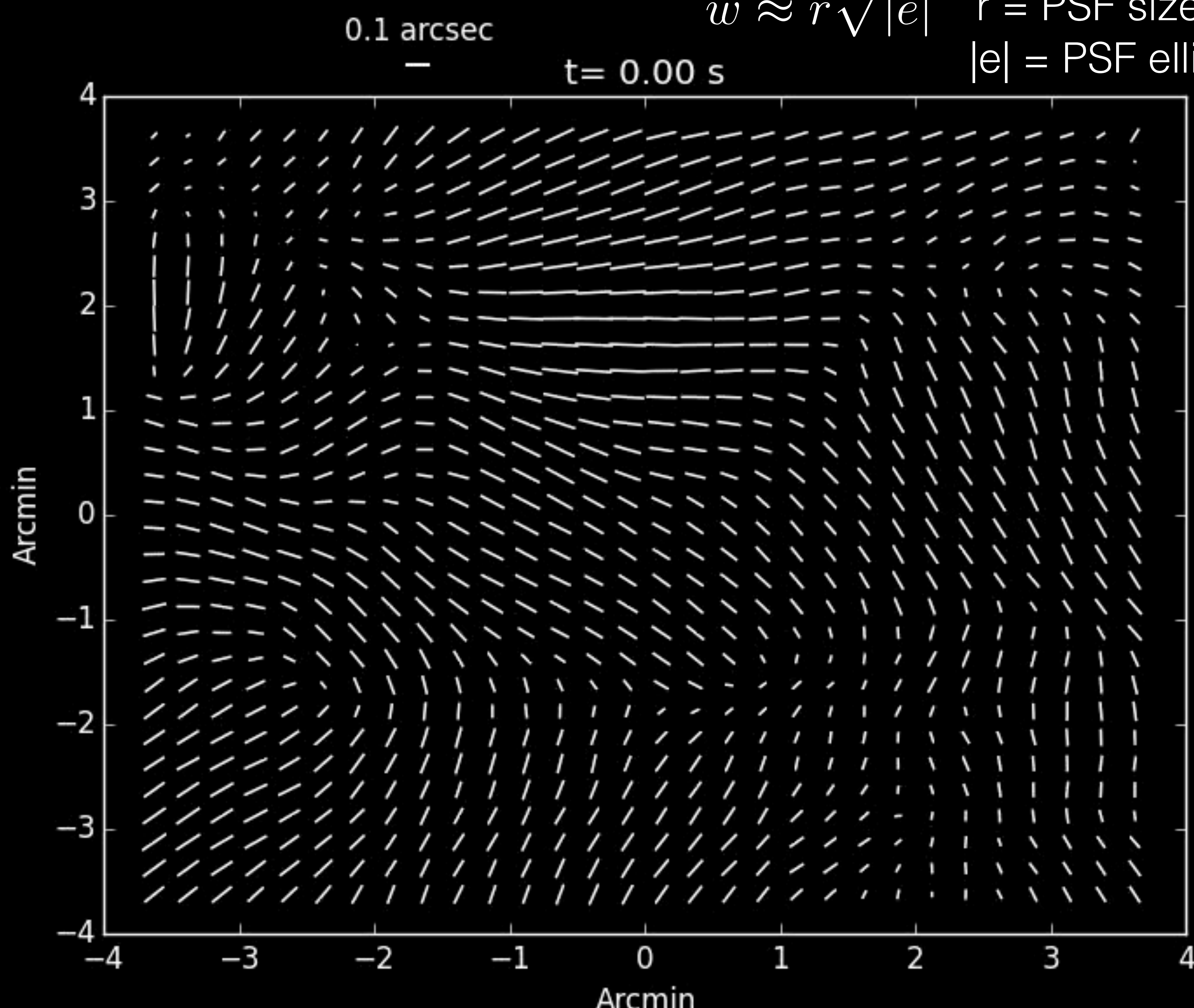
https://youtu.be/jzw5Kylfsws

PSF variation in time and space.

3 km

$w \approx r\sqrt{|e|}$ r = PSF size

|e| = PSF ellipticity magnitude



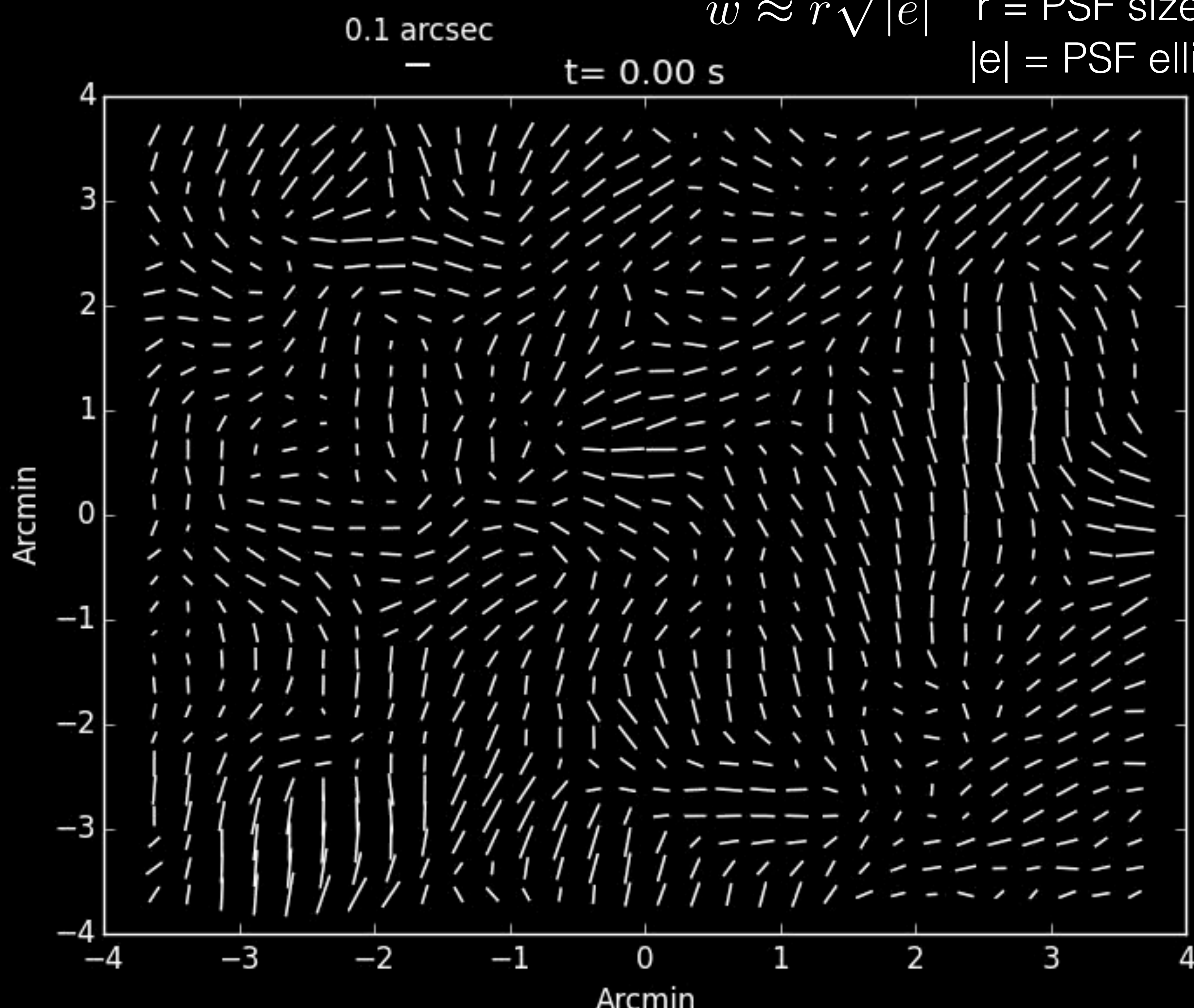
https://youtu.be/nT2sh3rBIjw

PSF variation in time and space.

10 km

$w \approx r\sqrt{|e|}$ r = PSF size

|e| = PSF ellipticity magnitude



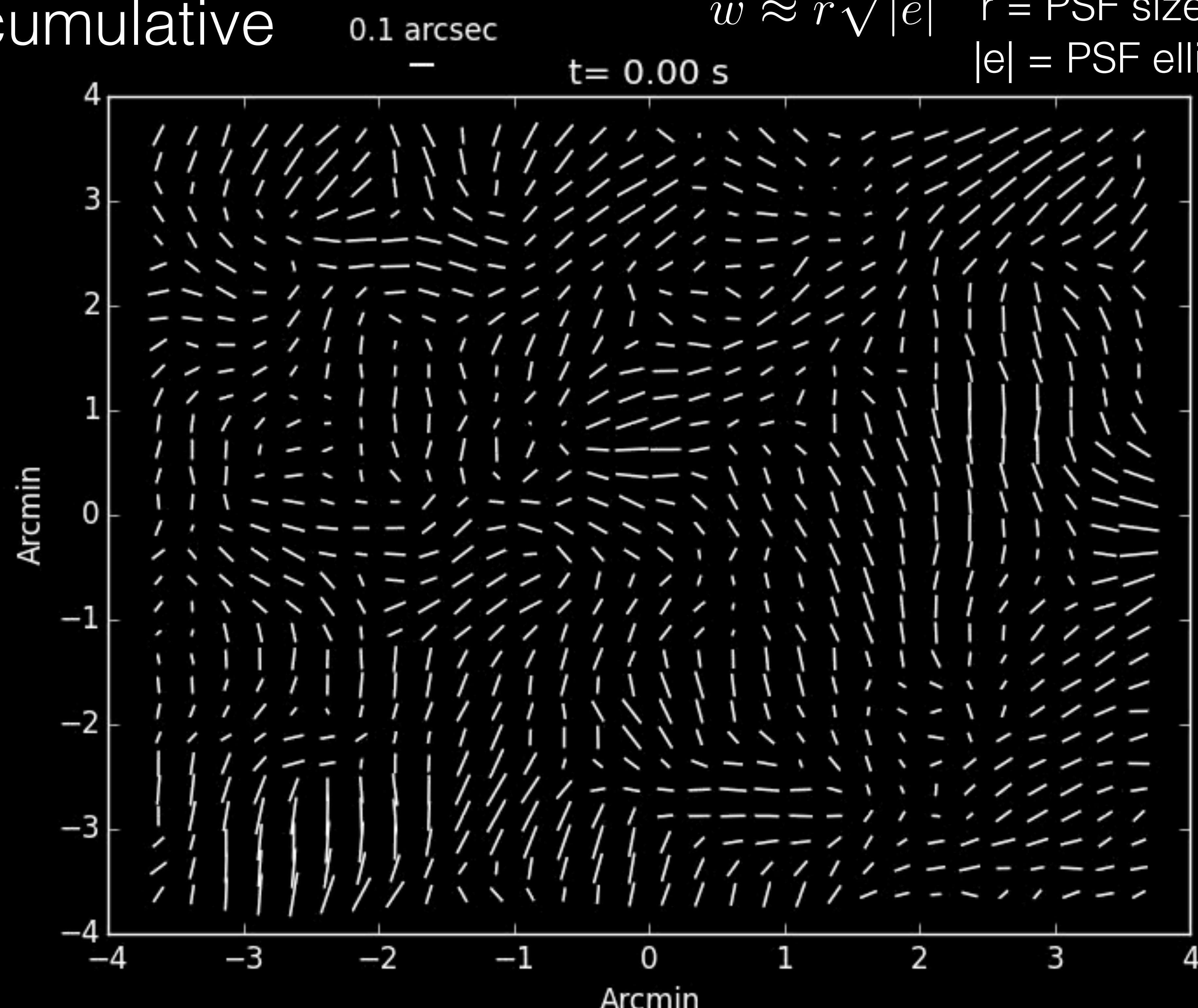
https://youtu.be/ccJSjNXTceI

PSF variation in time and space.

10 km cumulative

$w \approx r\sqrt{|e|}$ r = PSF size

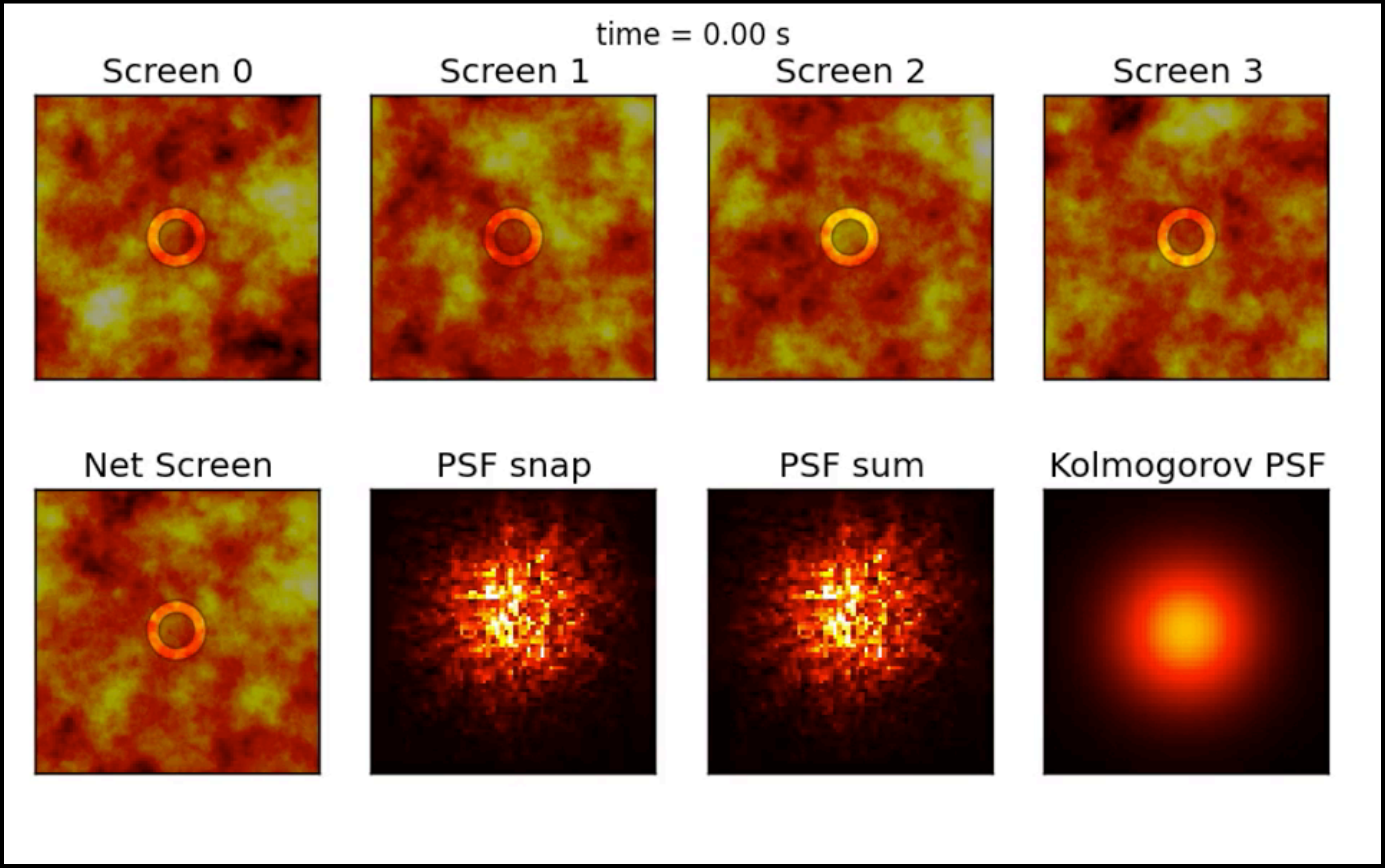
|e| = PSF ellipticity magnitude



https://youtu.be/xBFvKHkRmWQ

Boiling (Srinath et al. 2014)

$$W_i = \alpha W_{i-1} + \sqrt{1-\alpha^2} W_{\text{new}} \qquad \alpha \approx 0.997$$



https://youtu.be/_owV-vj6enU