Title: Deblurring Sgr A* Images

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Abstract: Scattering in the tenuous interstellar plasma blurs the image of Sgr A*. This effect decreases steeply with increasing frequency and becomes subdominant to the intrinsic emission structure at wavelengths close to a millimeter. I will discuss recent work that demonstrates how we can invert the blurring when properties of the scattering are known. With this technique, we can reconstruct the unscattered image of Sgr A* using EHT data. I will also show why some EHT observables -- such as closure phase and fractional polarization -- are largely immune to scattering. Finally, despite decades of study, there has been a recent flurry of progress in understanding the scattering properties, including studies of the Galactic Center magnetar and the discovery of refractive substructure in the scattering disk of Sgr A* at 1.3-cm wavelength. I will discuss these recent findings and their implications for imaging Sgr A* with the EHT

Deblurring Sgr A* Images

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EHT2014

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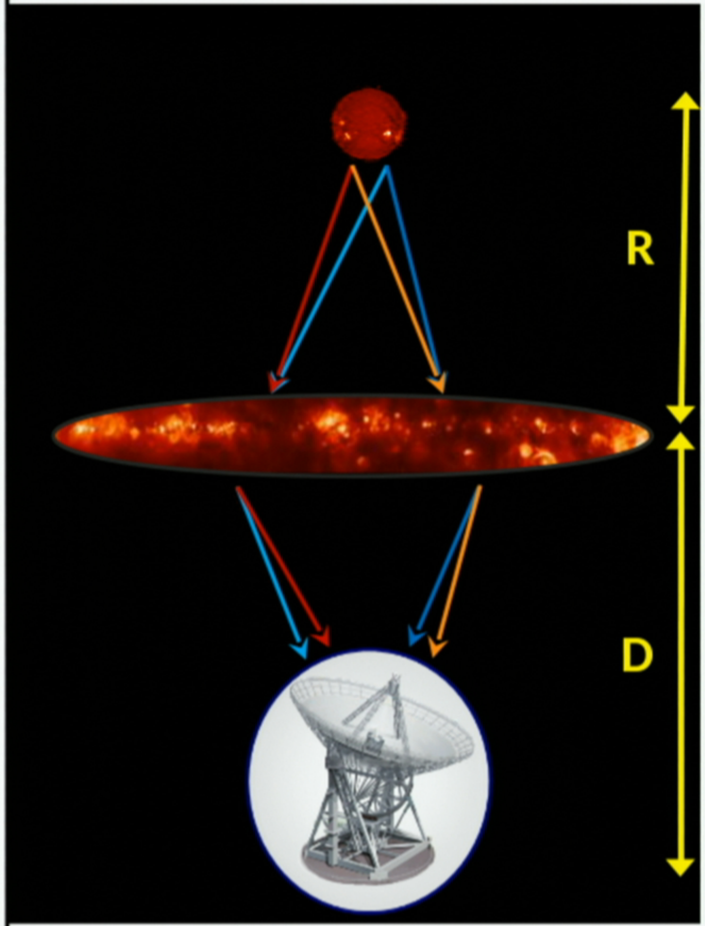
Interstellar Scattering



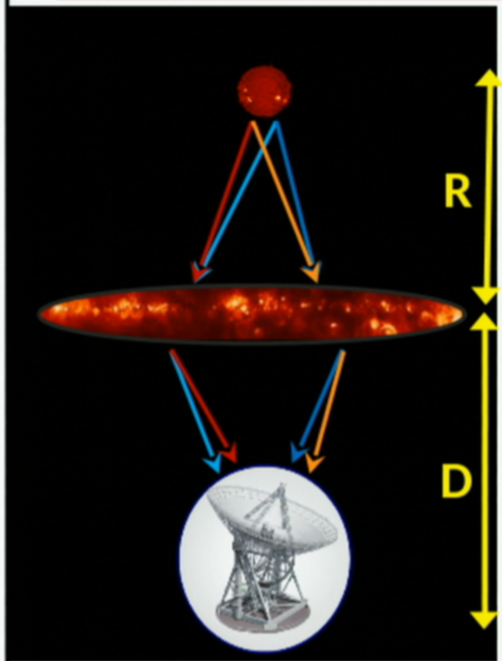
ISM density inhomogeneities scatter radio waves

Scattering is <u>stochastic</u>

Effects:

Angular Broadening
Temporal Broadening
Scintillation

Stars Twinkle, Planets Don't



A large source quenches the scintillation

- Point Source = <u>Snapshot</u> Image
- Large Source = <u>Average</u> Image
- Time Average = <u>Ensemble-Average</u> Image

Ensemble-average scattering is deterministic!

For the Air through which we look upon the Stars, is in a perpetual Tremor; as may be seen by the tremulous Motion of Shadows cast from high Towers, and by the twinkling of the fix'd Stars… Long Telescopes may cause Objects to appear brighter and larger than short ones can do, but they cannot be so formed as to take away that confusion of the Rays which arises from the Tremors of the Atmosphere. – Newton, *Opticks*

The Phase Structure Function

Scattering can be described by a “thin-screen” that imparts a stochastic, position-dependent phase

The phase structure function conveniently parametrizes the scattering:

$$D_{\phi}(\mathbf{x}) \equiv \left\langle \left[\phi(\mathbf{x}+\mathbf{x}') - \phi(\mathbf{x}')\right]^2 \right\rangle$$

Real, positive, symmetric

Need:

Injection (outer) scale of the turbulence
Power-law index in the inertial range
Dissipation (inner) scale of the turbulence

The Ensemble-Average Image

For interferometry, the ensemble-average image of a point source is closely related to the structure function:

$$\tilde{I}(\mathbf{u}) = \exp\left[-\frac{1}{2} D_\phi \left(\frac{\lambda \mathbf{u}}{1+M}\right)\right]$$

Scattering Kernel

Visibility Baseline

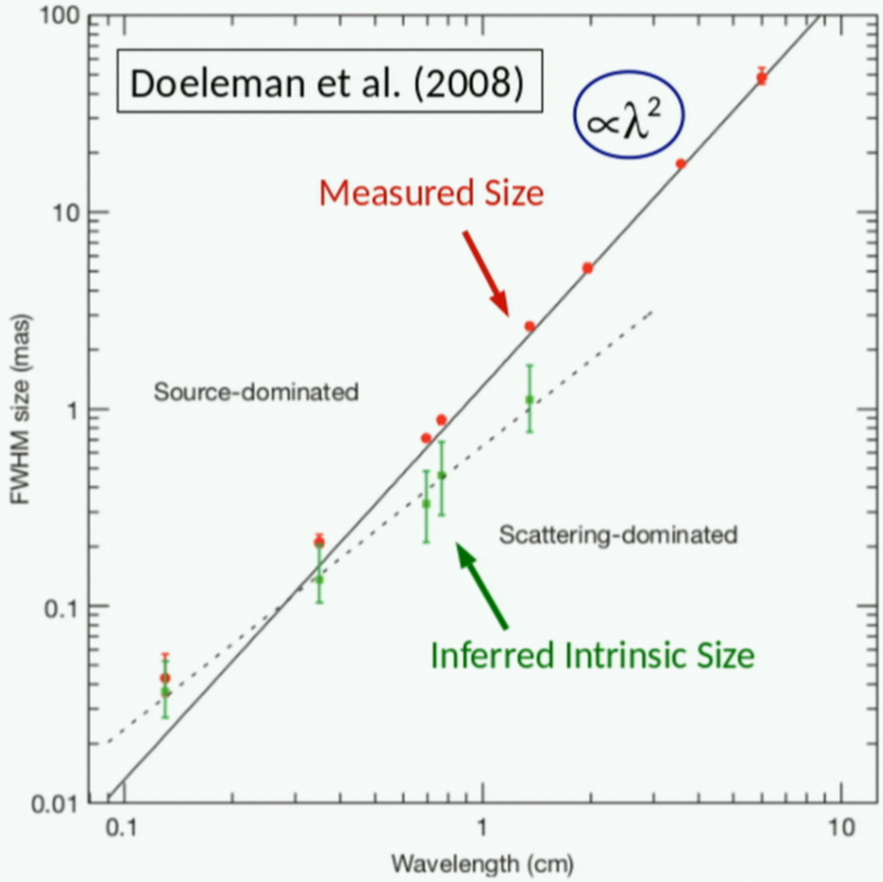
Magnification

For an extended source, scattering simply acts as a convolution

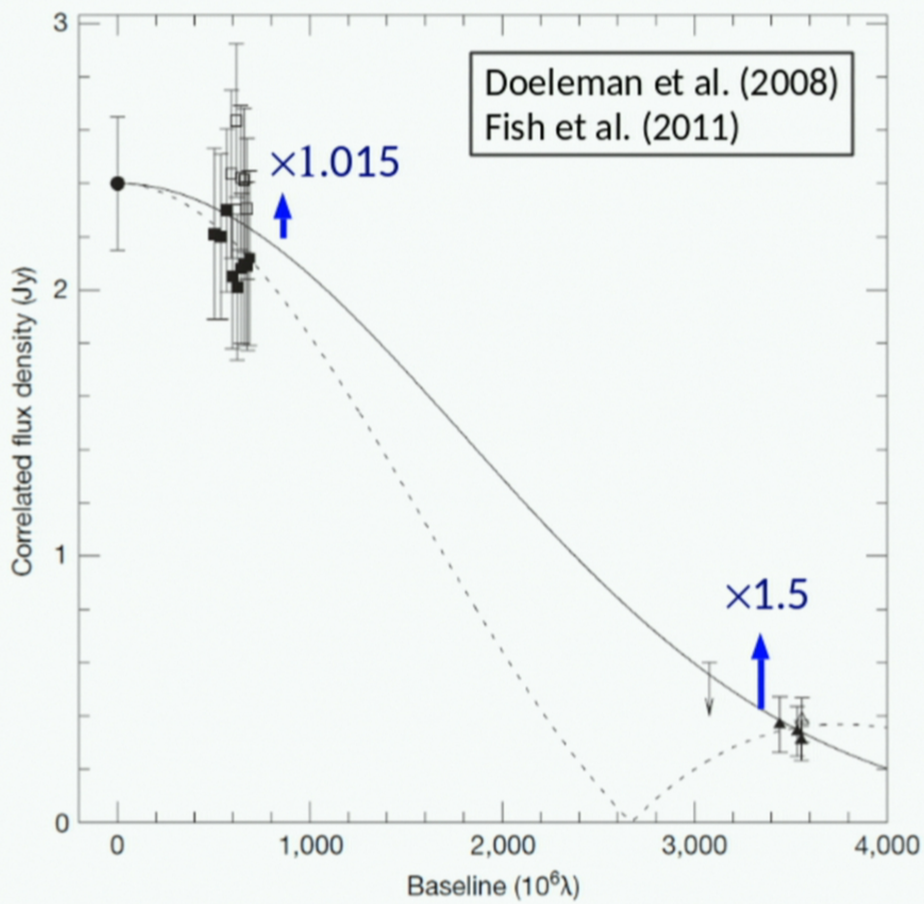
Result: **The image** is uniformly blurred
The visibilities are multiplied by the point-source response (kernel)

Also: Some VLBI quantities are unaffected!

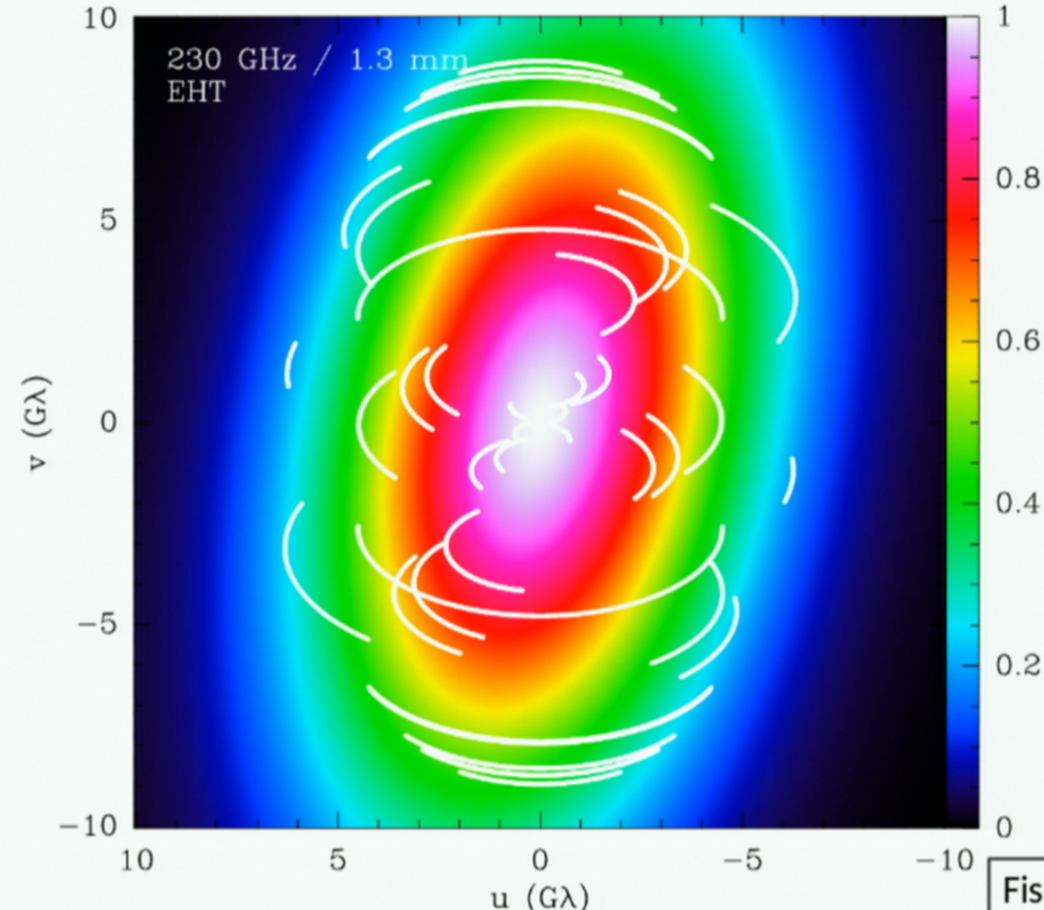
Sgr A*: Observed Size vs. Wavelength



Sgr A* with 1.3-mm VLBI

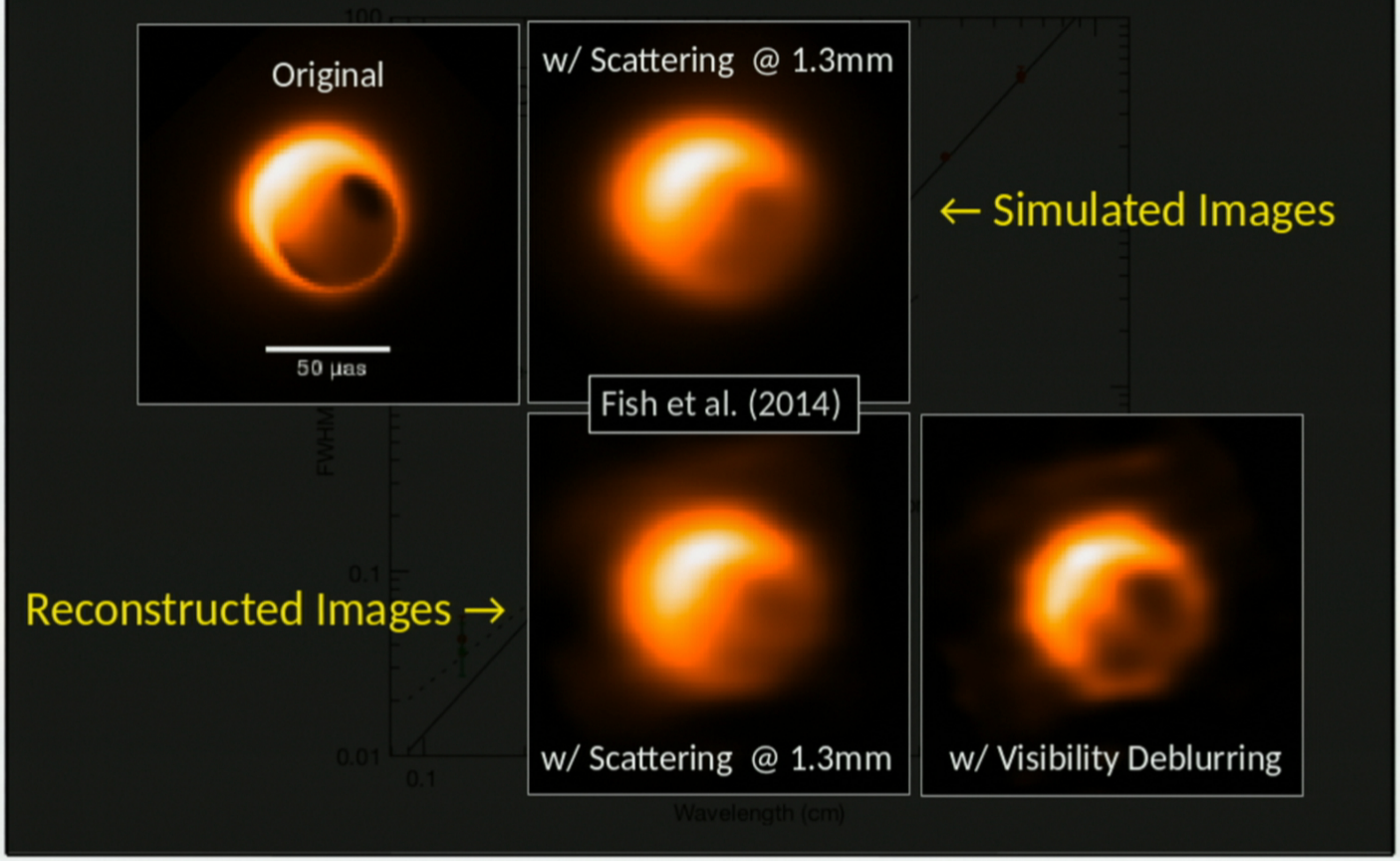


The Scattering Kernel at 230 GHz

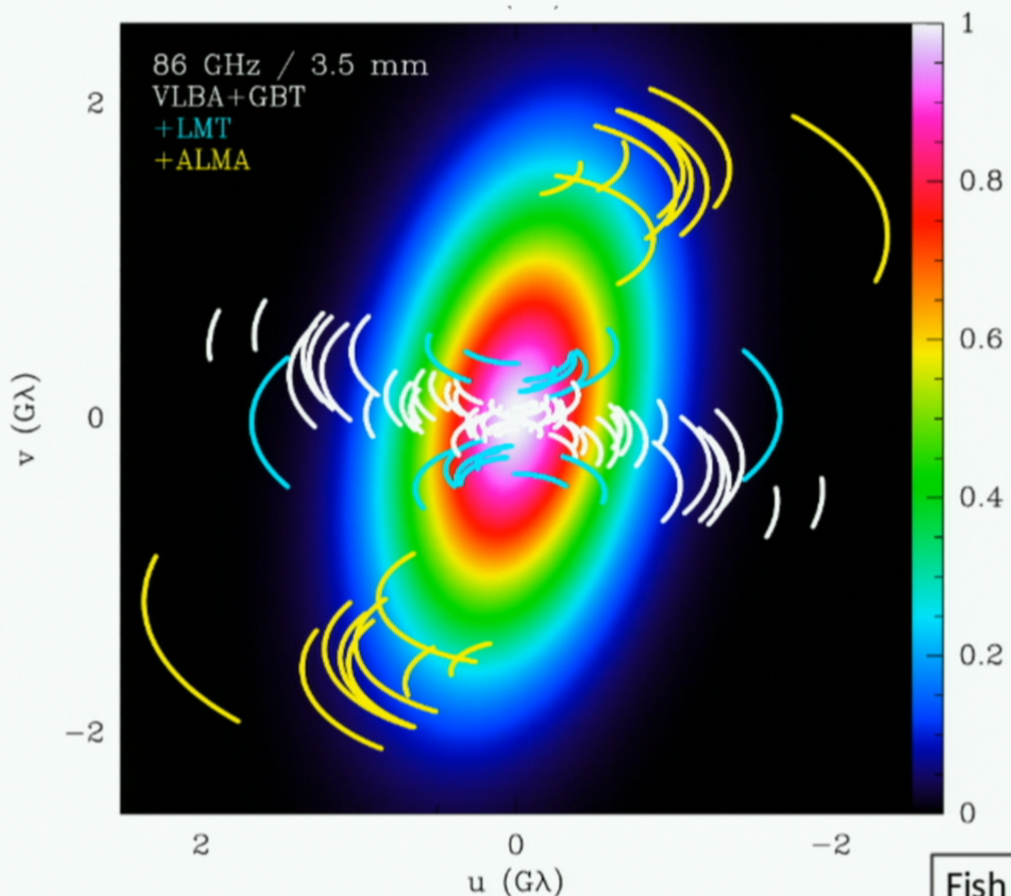


Fish et al. (2014)

Deblurring Images of Sgr A*



The Scattering Kernel at 86 GHz



Fish et al. (2014)

Summary

Blurring from scattering is deterministic and invertible

Scattering = Amplified Thermal Noise (no more than $\times 5$ on EHT baselines)

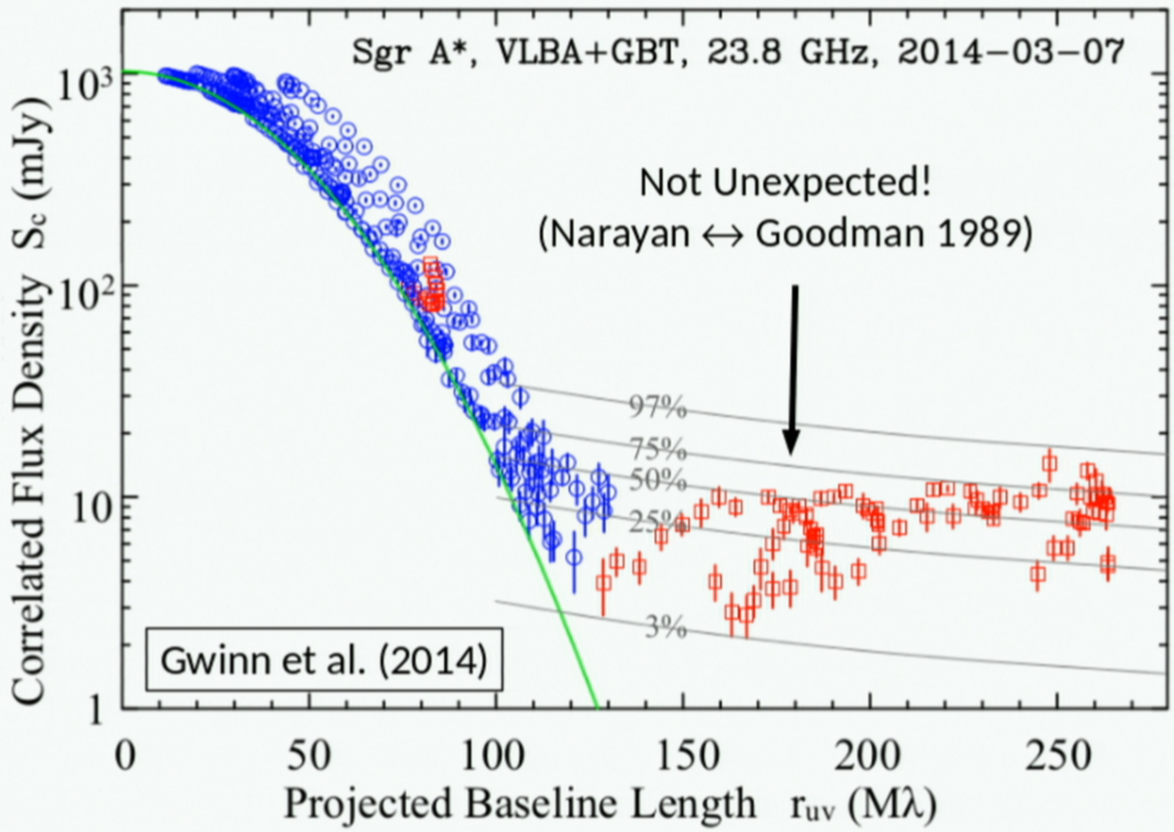
Mitigation Strategy:

1. Divide sampled visibilities by known kernel
2. Image using the re-scaled visibilities
3. Result gives the unscattered image

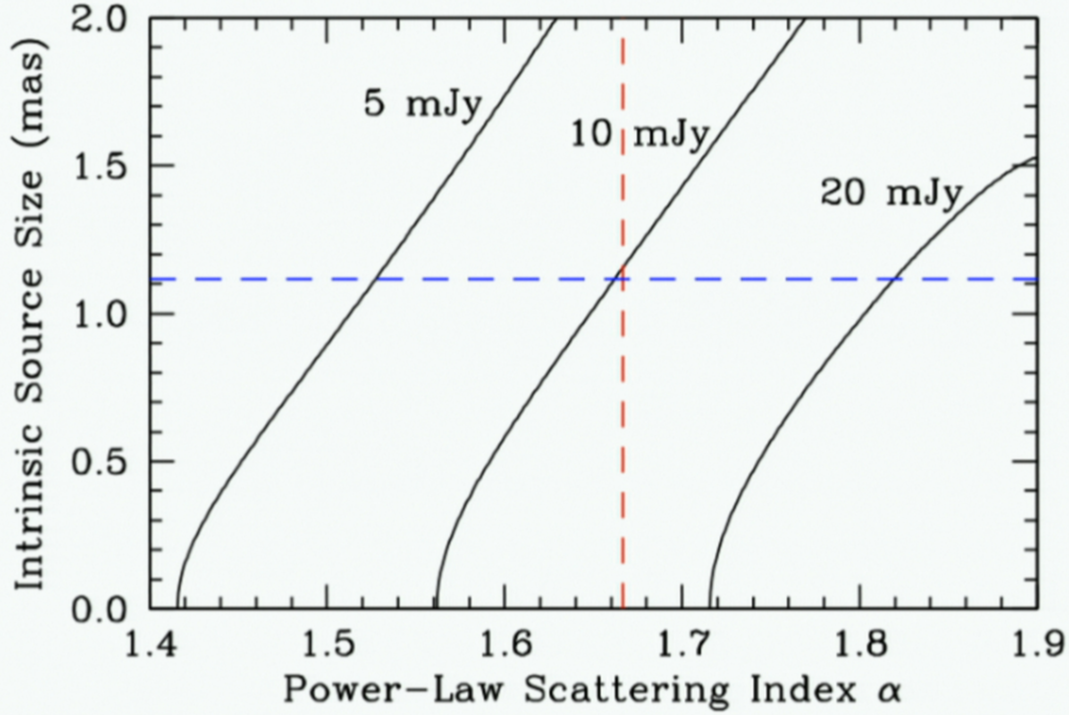
Limitations:

1. Do we know the scattering kernel?
2. Is the ensemble-average regime a good approximation?

Refractive Substructure at 1.3 cm

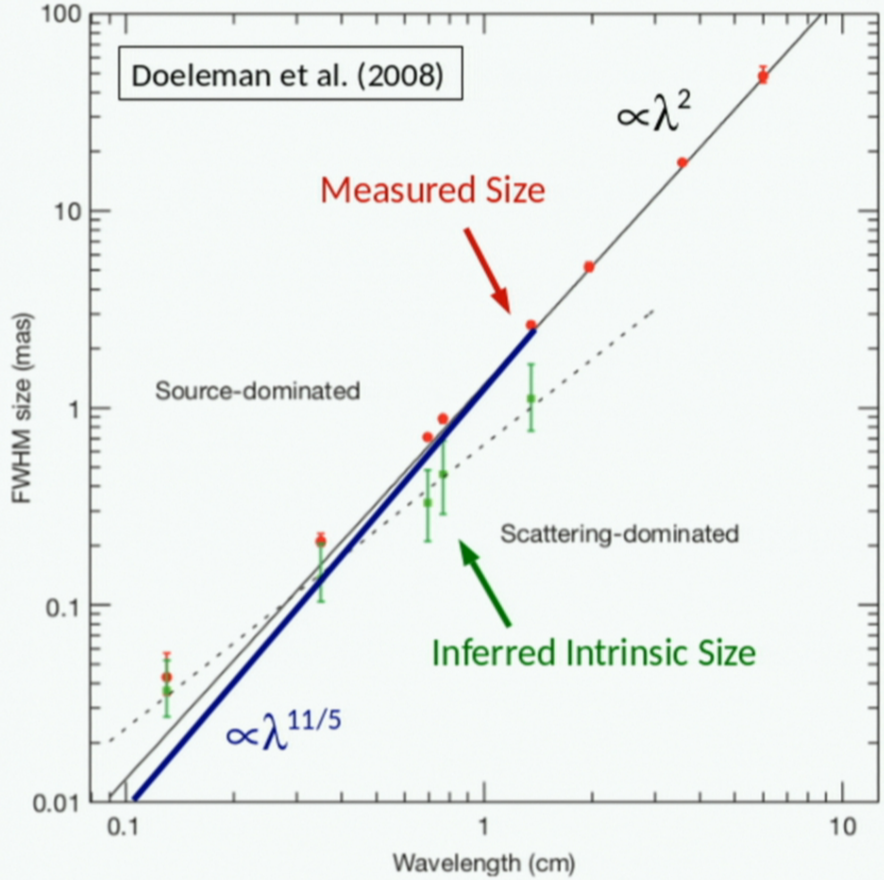


Refractive Substructure at 1.3 cm



Gwinn et al. (2014)

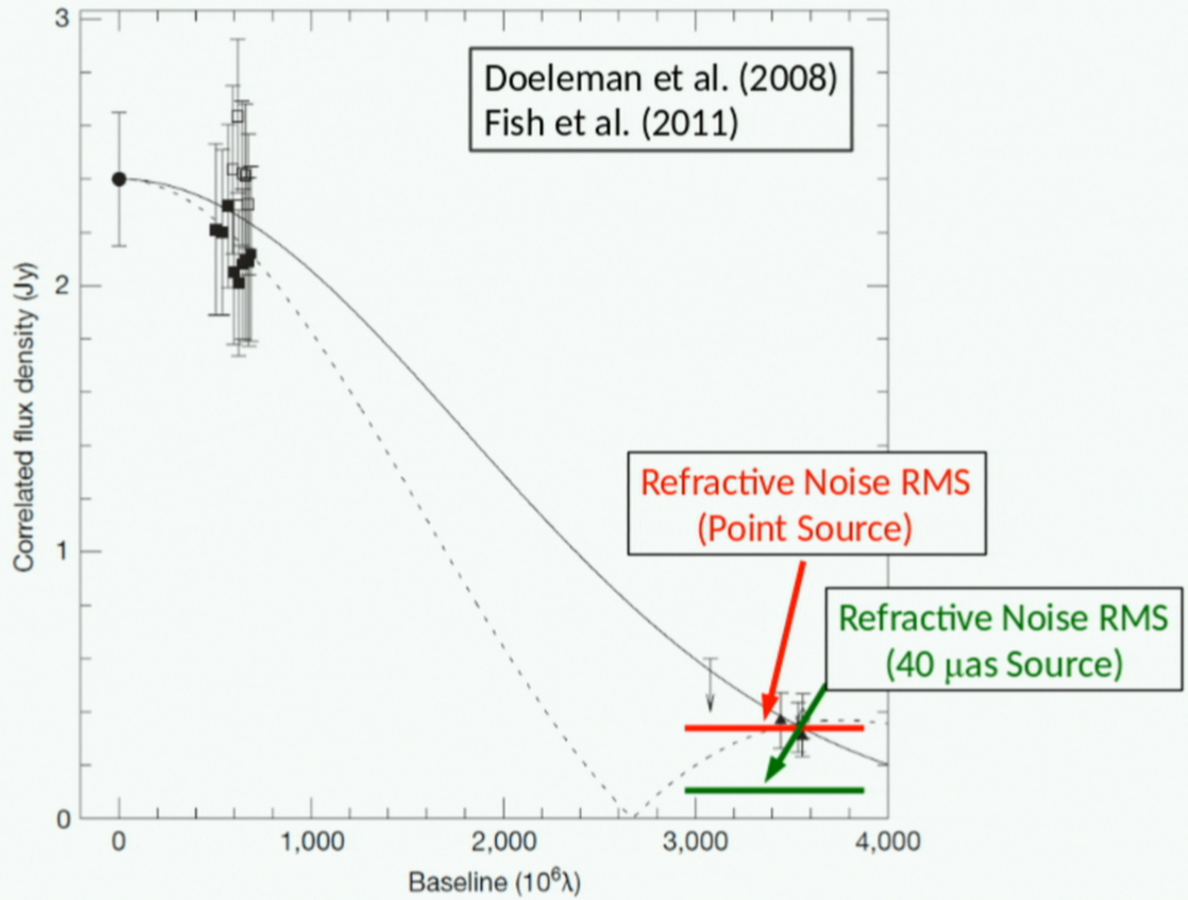
A Shallow Spectrum?



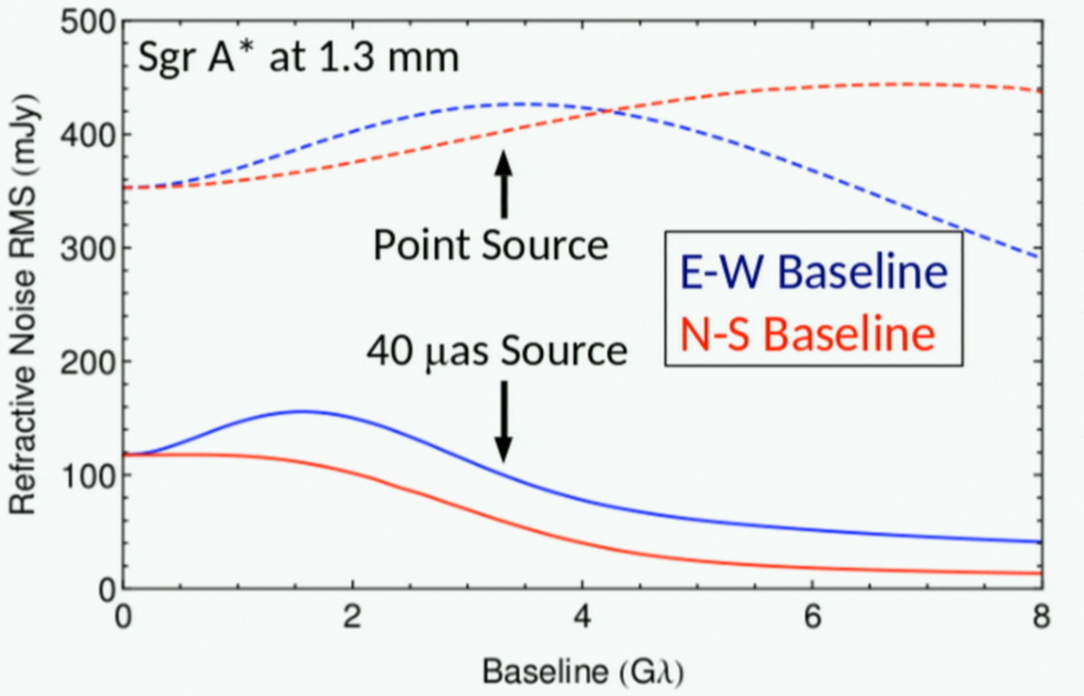
Shallow Spectrum
= Weaker Scattering

Important for deconvolution, especially on long baselines!

Sgr A* with 1.3-mm VLBI



Expected Refractive Noise



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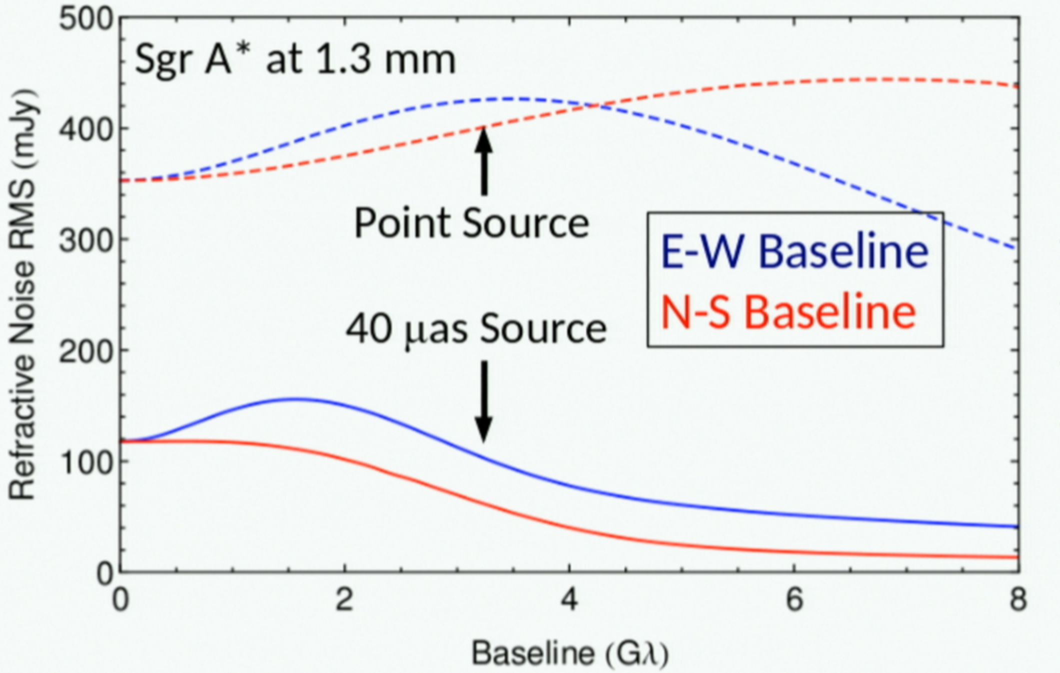

But the refractive noise is correlated on EHT baselines

Leading Effect: Flux variations (easy to normalize)
Next Effect: Image wander (not immediately relevant)

The Role of Simulations

Idea (Narayan & Goodman 1989):

Make a scattering screen (an array of correlated random phases)

Do the Fresnel scattering integral (Source + Screen + Observing Plane)

2D:

For Sgr A* at 1.3 cm: (10^15 screen phases)x(4-dim integral) per baseline

1.3 mm: (10^9 screen phases)x(4-dim integral) per baseline

But, analytical results for special cases!

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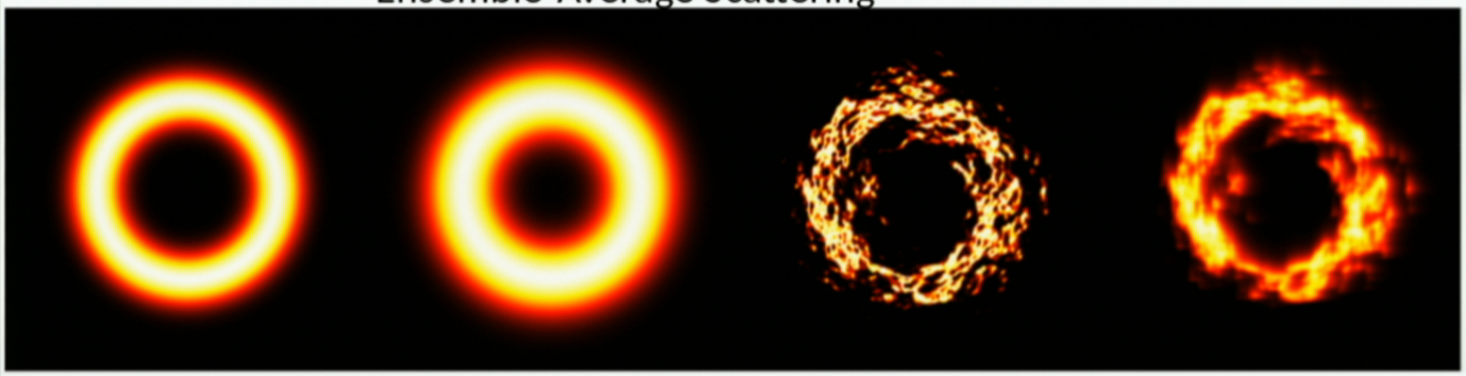
How Does Refractive Substructure Look?

Unscattered Source

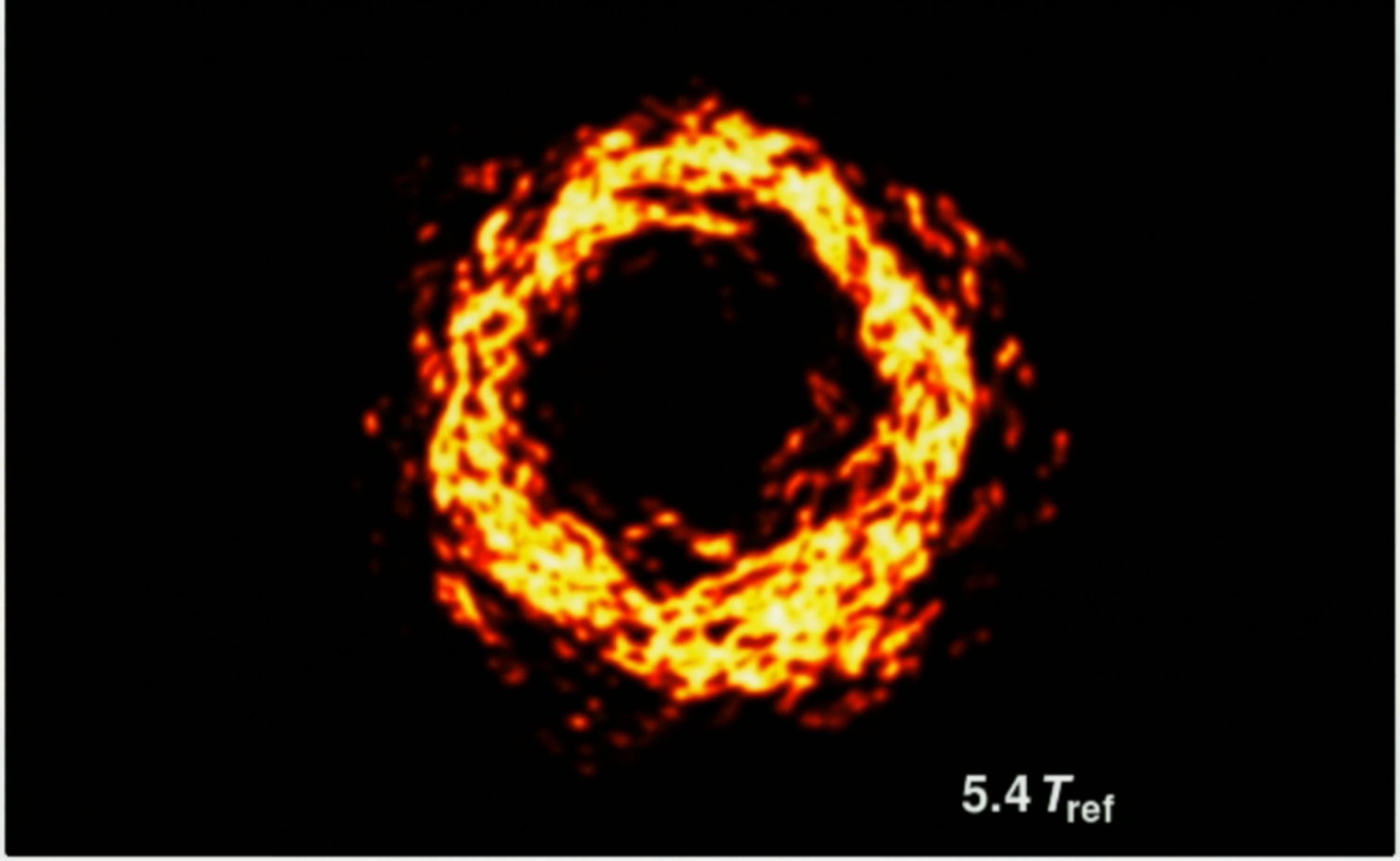
Ensemble-Average Scattering



High-Resolution Low-Resolution

"Snapshot" Scattered Source
= Average-Image Regime

How Does Refractive Substructure Look?



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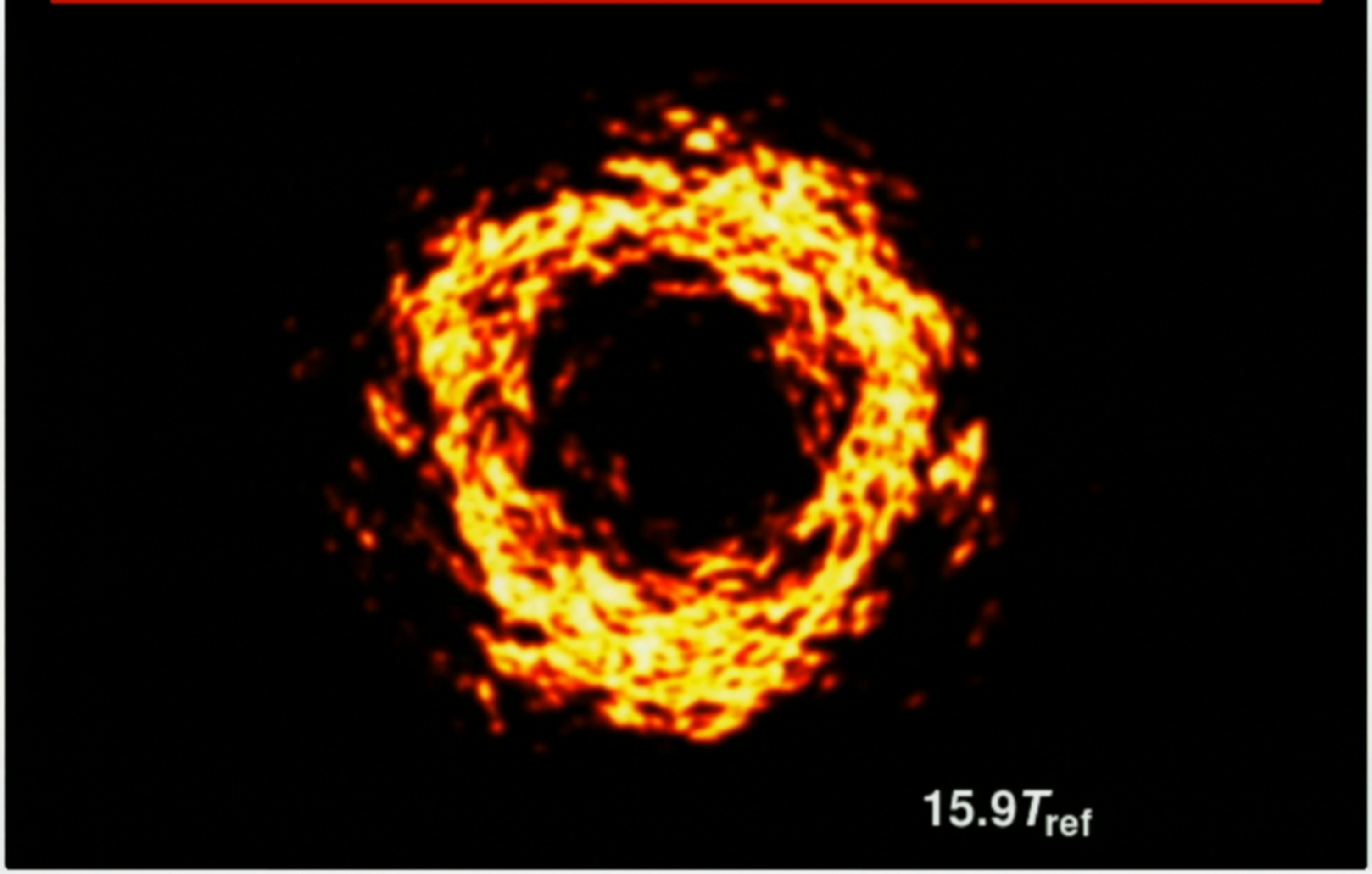

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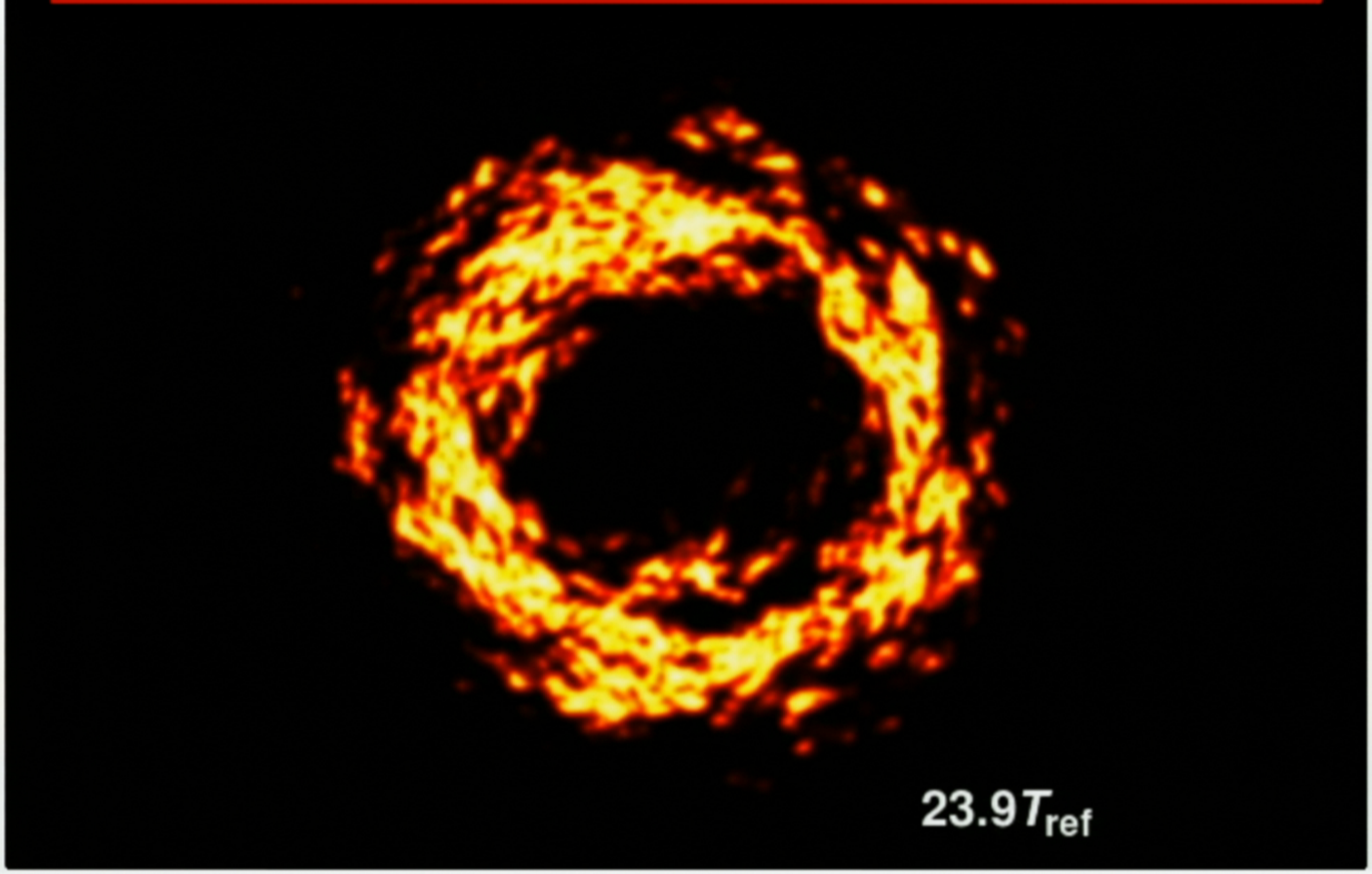
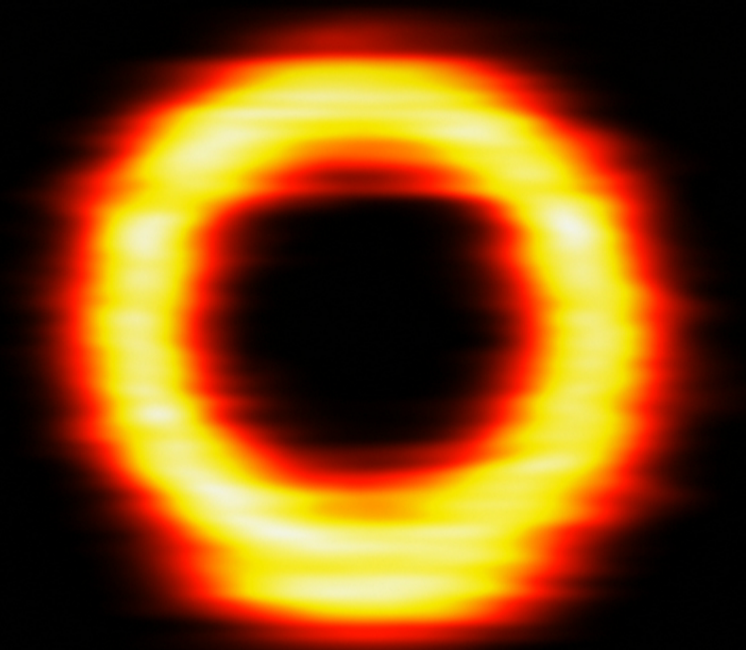


How Does Refractive Substructure Look?

Movie Average:



≈ Ensemble-Average Image
(suitable for deblurring)

Summary

Scattering is important to understand and is still providing surprises

The dominant effect is blurring

Invertible

Just added noise (if known kernel)

The sub-dominant effect is substructure

Averaging still gives ensemble average (see poster: Freek Roelofs)

Variations can distort single-epoch images

$\lesssim$ 100 mJy noise seems a likely <u>fundamental limit</u>

Further mitigation techniques needed!

What is the relative strength of GR tests with M87?

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Scattering is important to understand and is still providing surprises

The dominant effect is blurring

- Invertible
- Just added noise (if known kernel)

The sub-dominant effect is substructure

- Averaging still gives ensemble average (see poster: Freek Roelofs)
- Variations can distort single-epoch images
- $\lesssim$ 100 mJy noise seems a likely <u>fundamental limit</u>
- Further mitigation techniques needed!

What is the relative strength of GR tests with M87?