Mitigating the Effects of Interstellar Scattering for VLBI

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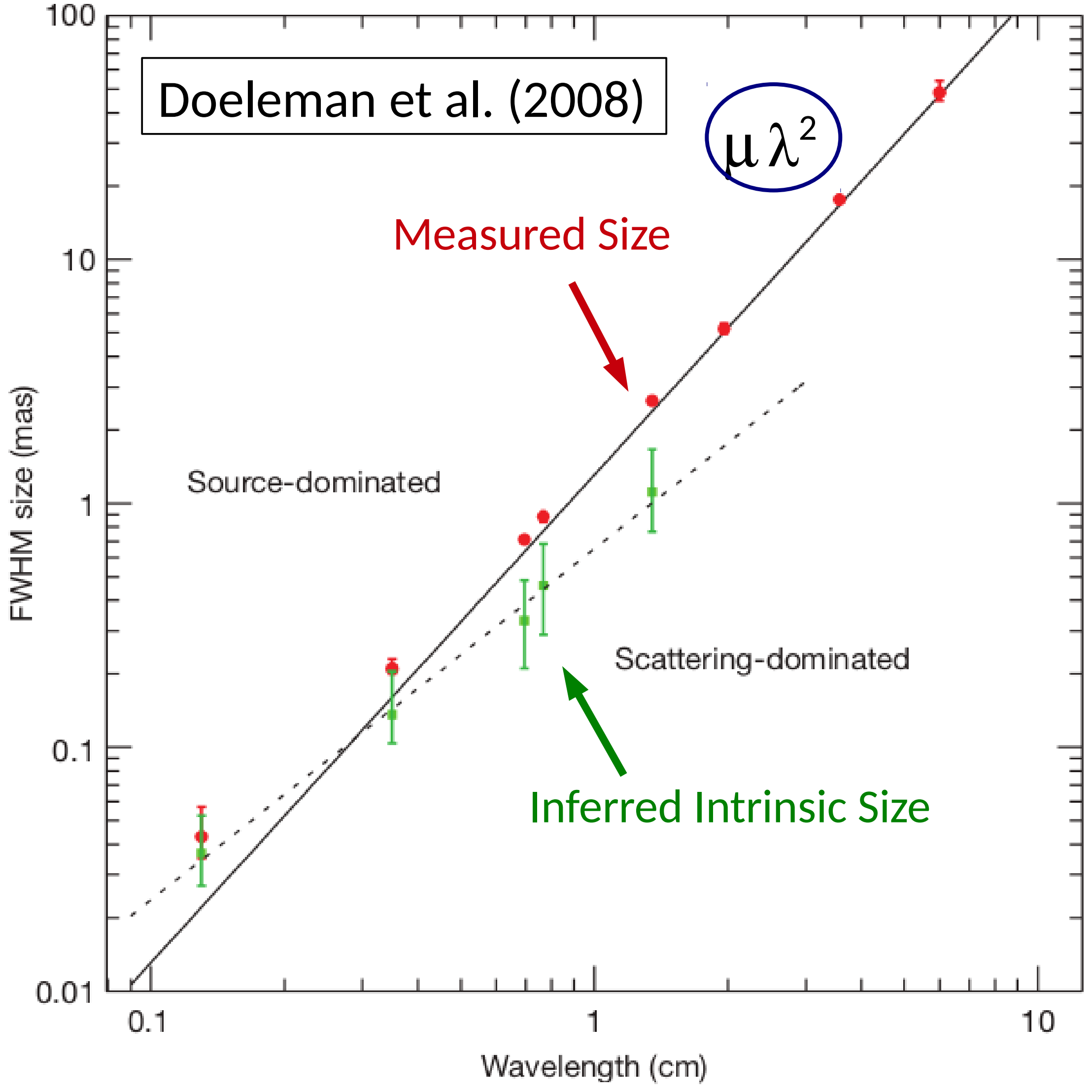
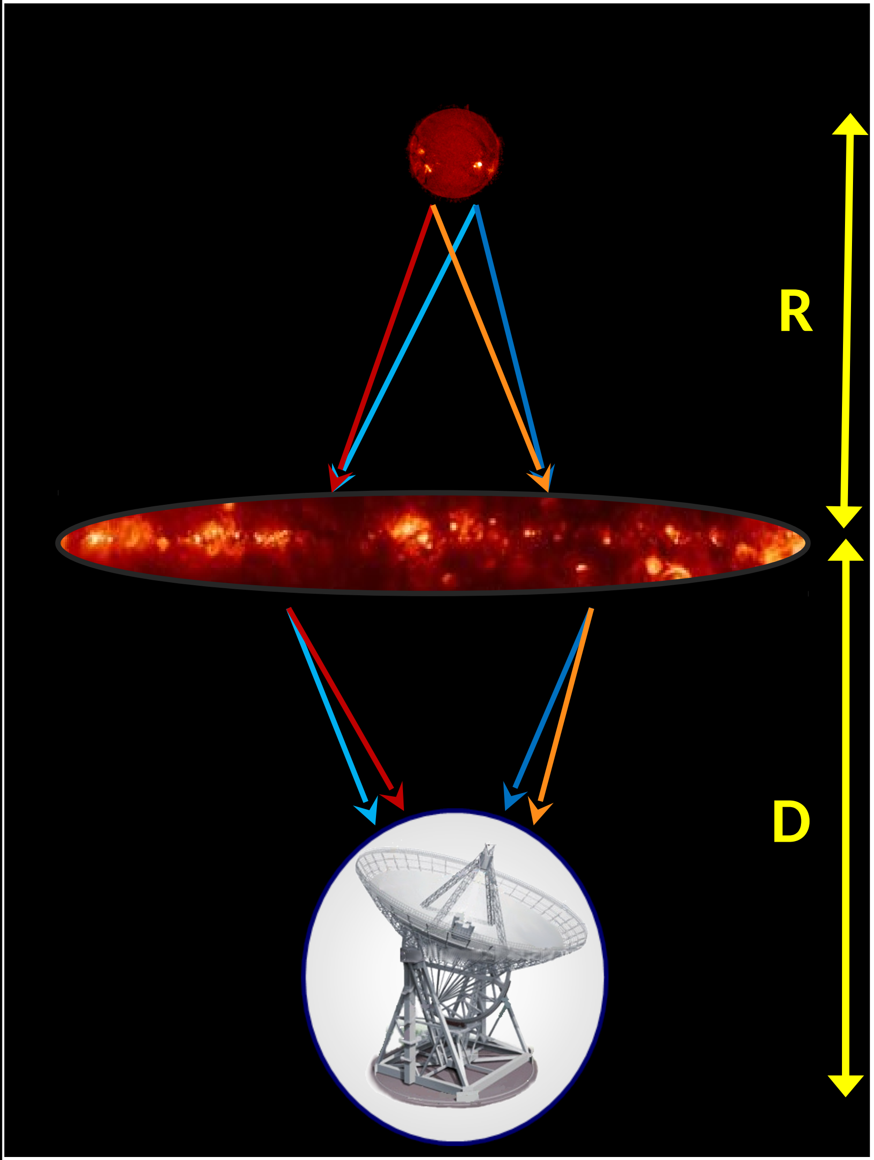
Sgr A*: Observed Size vs. Wavelength



Interstellar Scattering



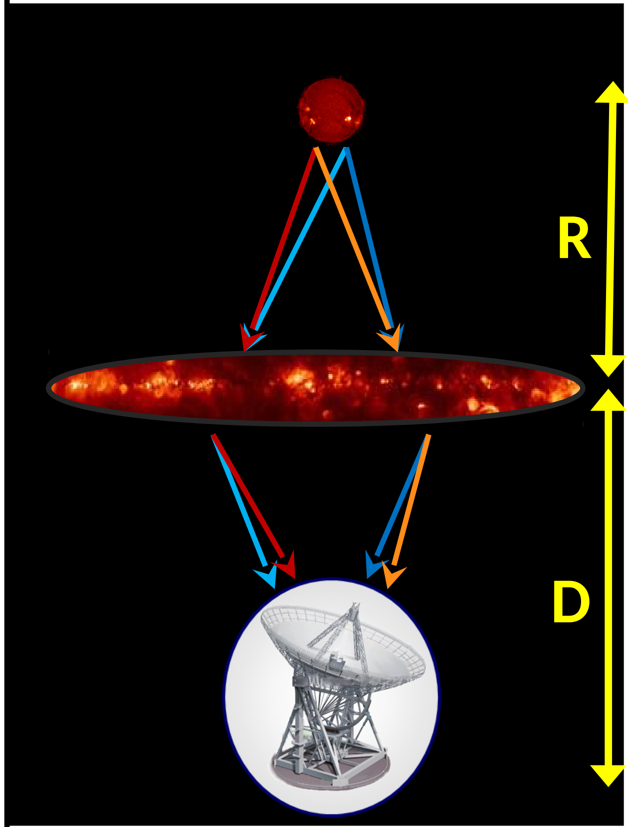
ISM density inhomogeneities scatter radio waves

Scattering is <u>stochastic</u>

Effects:

- Angular Broadening
- Temporal Broadening
- Scintillation

Stars Twinkle, Planets Don't



A large source quenches the scintillation

- Point Source = Snapshot Image
- Large Source = Average Image
- Time Average = Ensemble-Average 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:

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

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

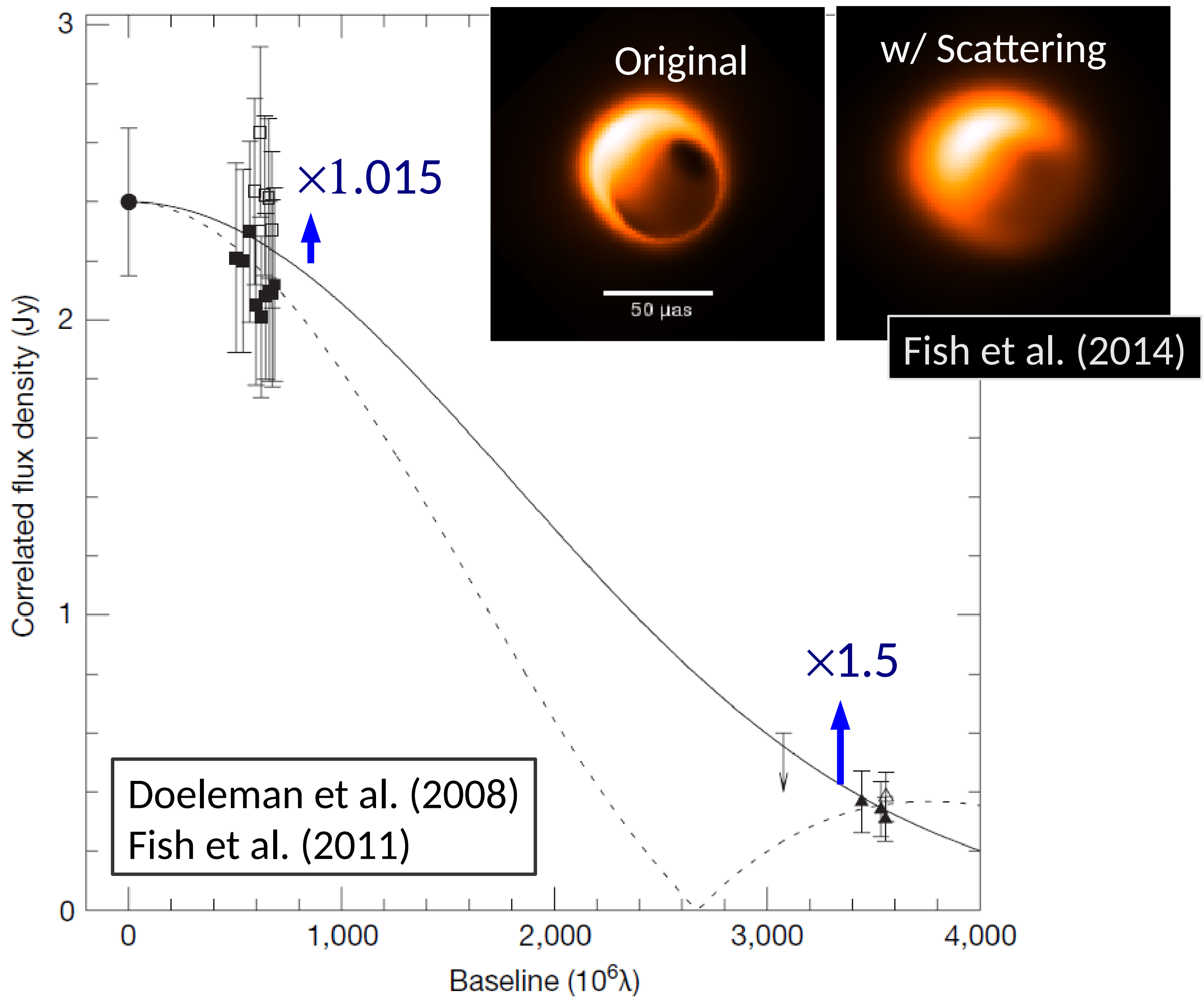
For an extended source, scattering simply acts as a convolution

Result: **The image** is uniformly <u>blurred</u>

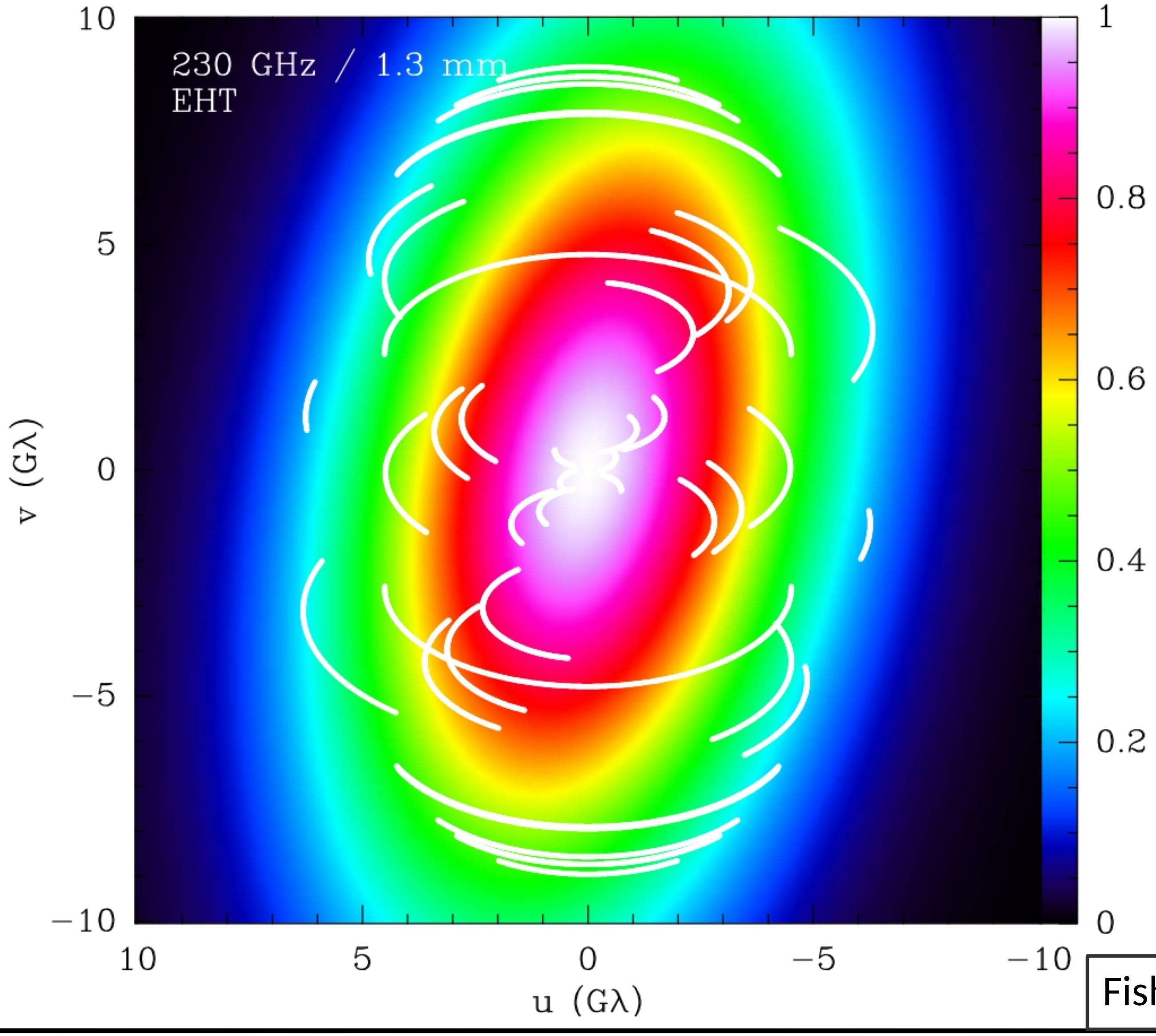
The visibilities are <u>multiplied</u> by the point-source response (kernel)

Also: Some VLBI quantities are unaffected!

How Does the Scattered Image Look?

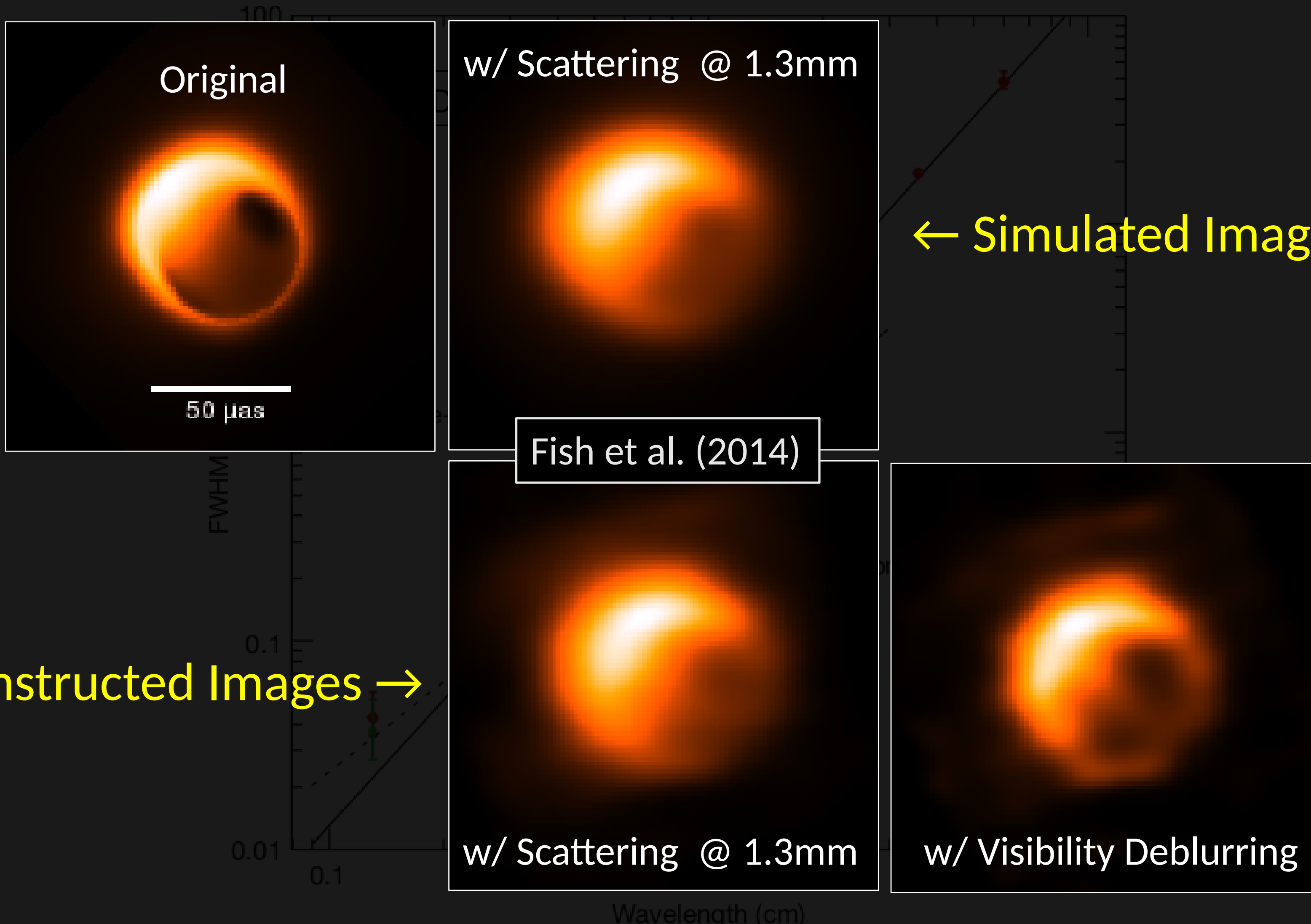


The Scattering Kernel at 230 GHz



Fish et al. (2014)

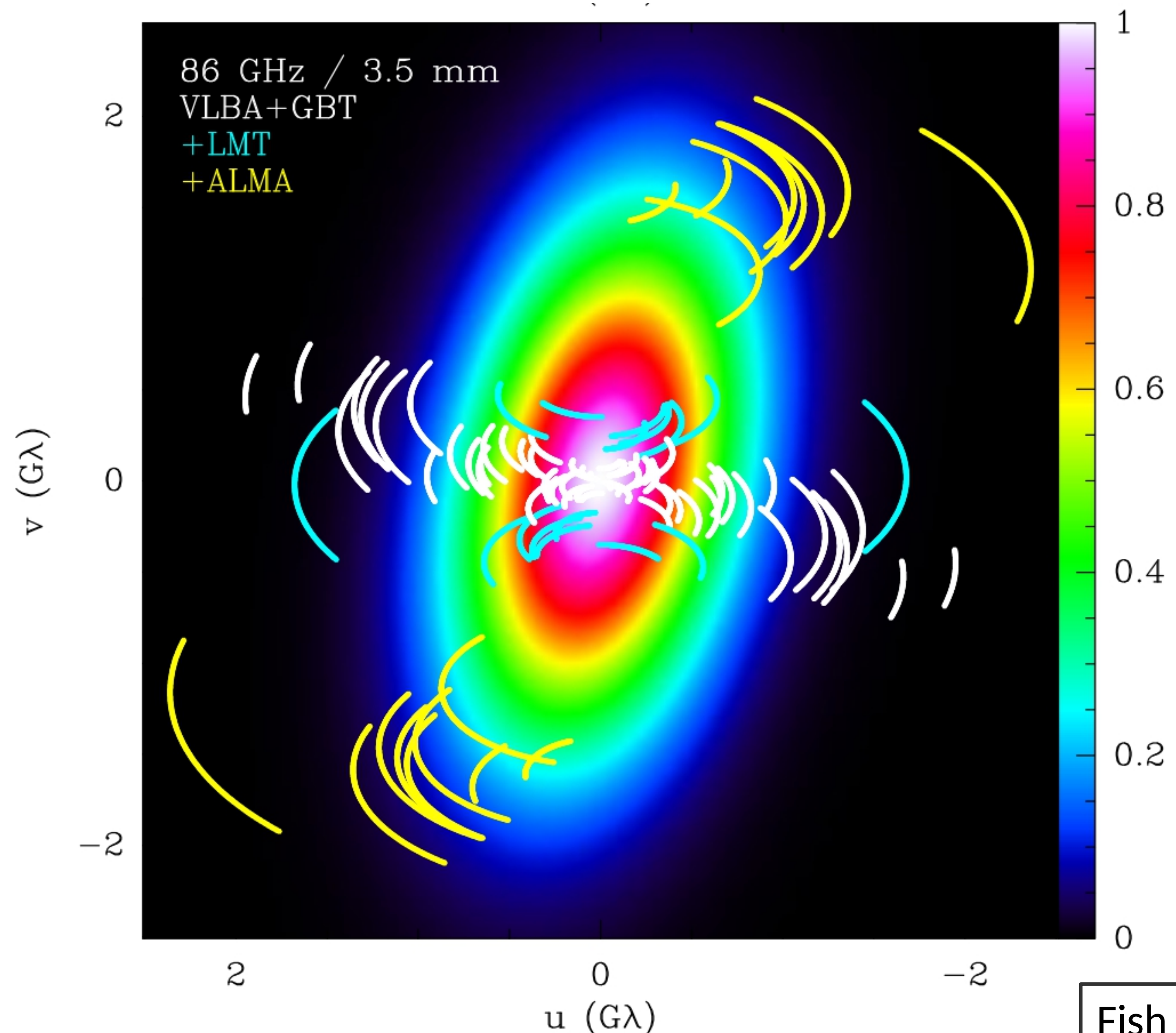
Deblurring Images of Sgr A*



← Simulated Images

Reconstructed Images →

The Scattering Kernel at 86 GHz



Fish et al. (2014)

Summary

Blurring from scattering is <u>deterministic</u> and <u>invertible</u>

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 <u>unscattered</u> image

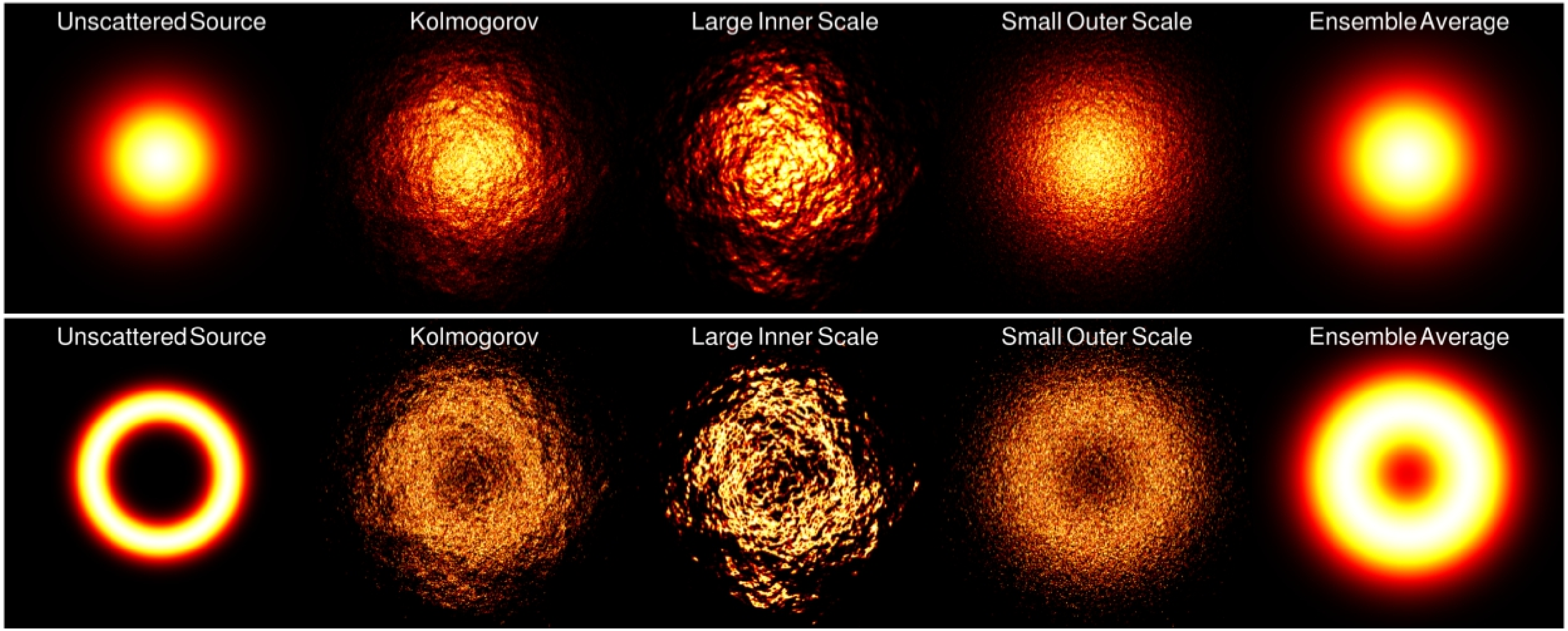
Limitations:

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

How Does the Actual Image Look?

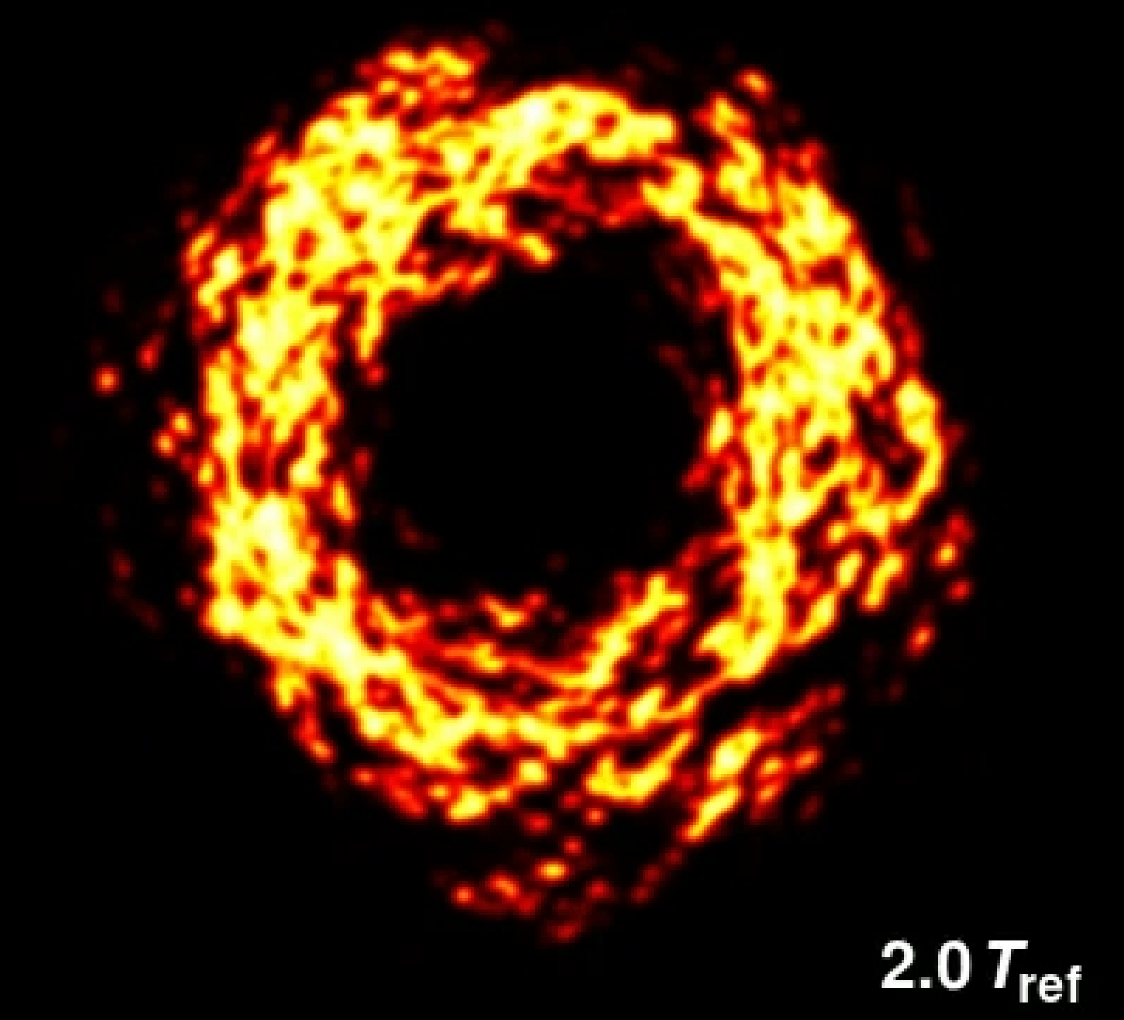
In the ensemble-average regime the image is blurred

What is the appearance for a realistic (incomplete) average?



Johnson & Gwinn (2015)

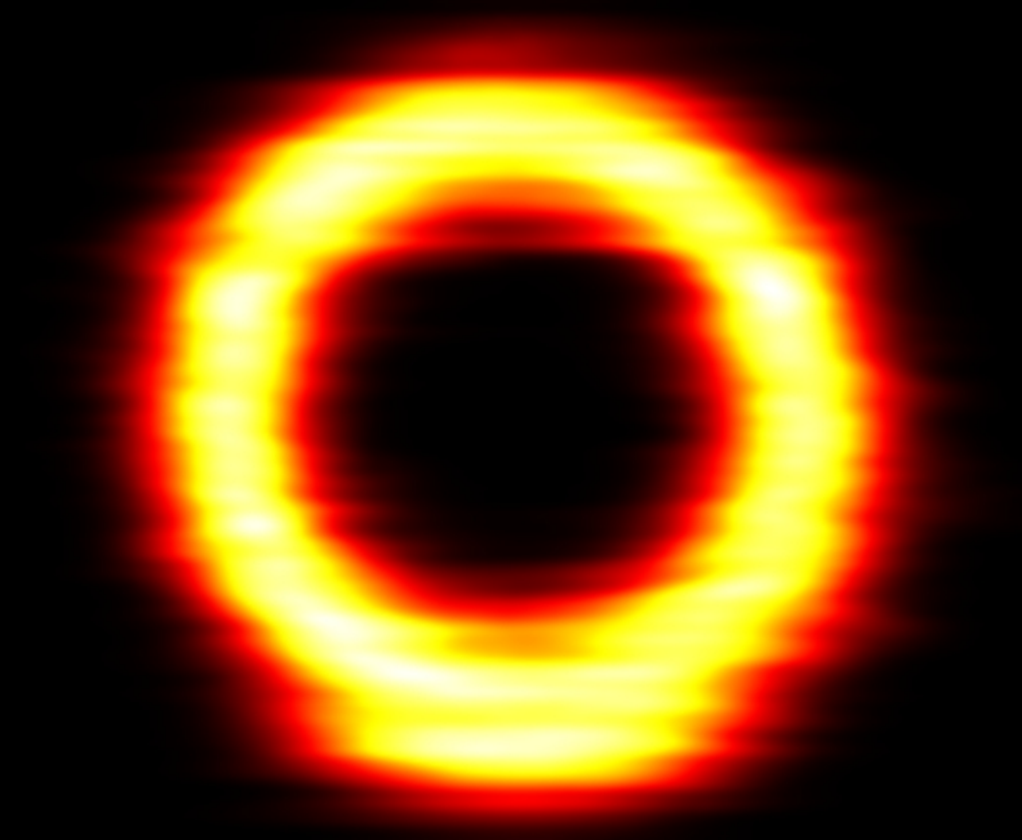
How Does the Actual Image Look?



T_{ref} ~ 1 Day

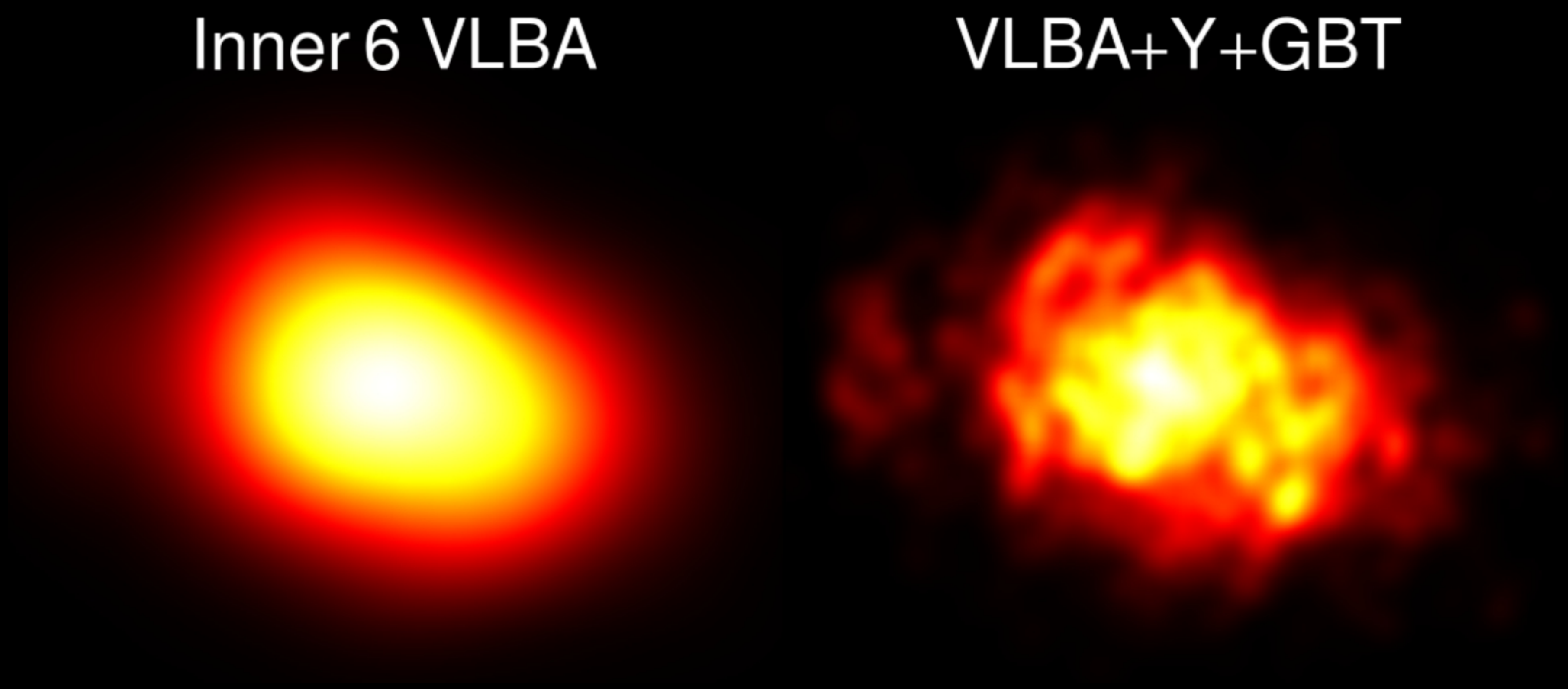
How Does the Actual Image Look?

Movie Average:



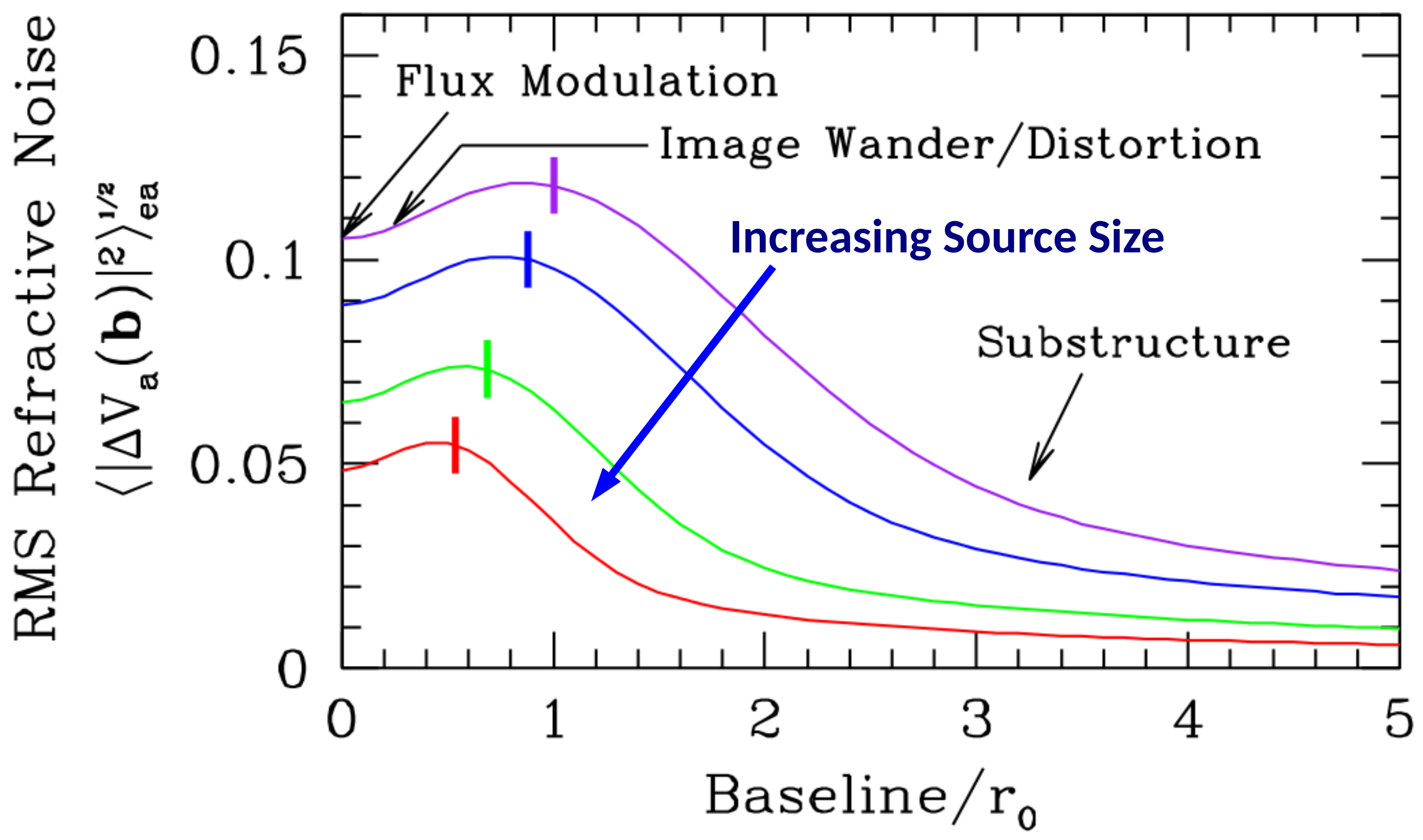
≈ Ensemble-Average Image
(suitable for deblurring)

Sgr A* at 1.3 cm



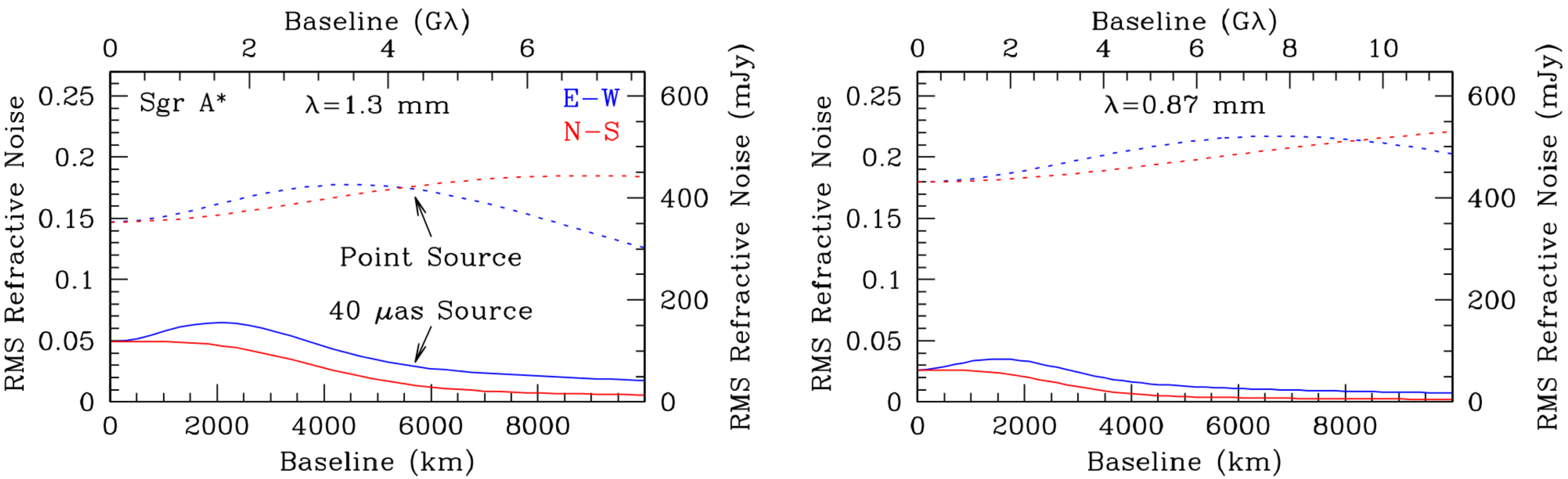
Example Images from Simulations

Refractive Effects Depend on Baseline



Johnson & Gwinn (2015)

Expected Refractive Noise for Sgr A*

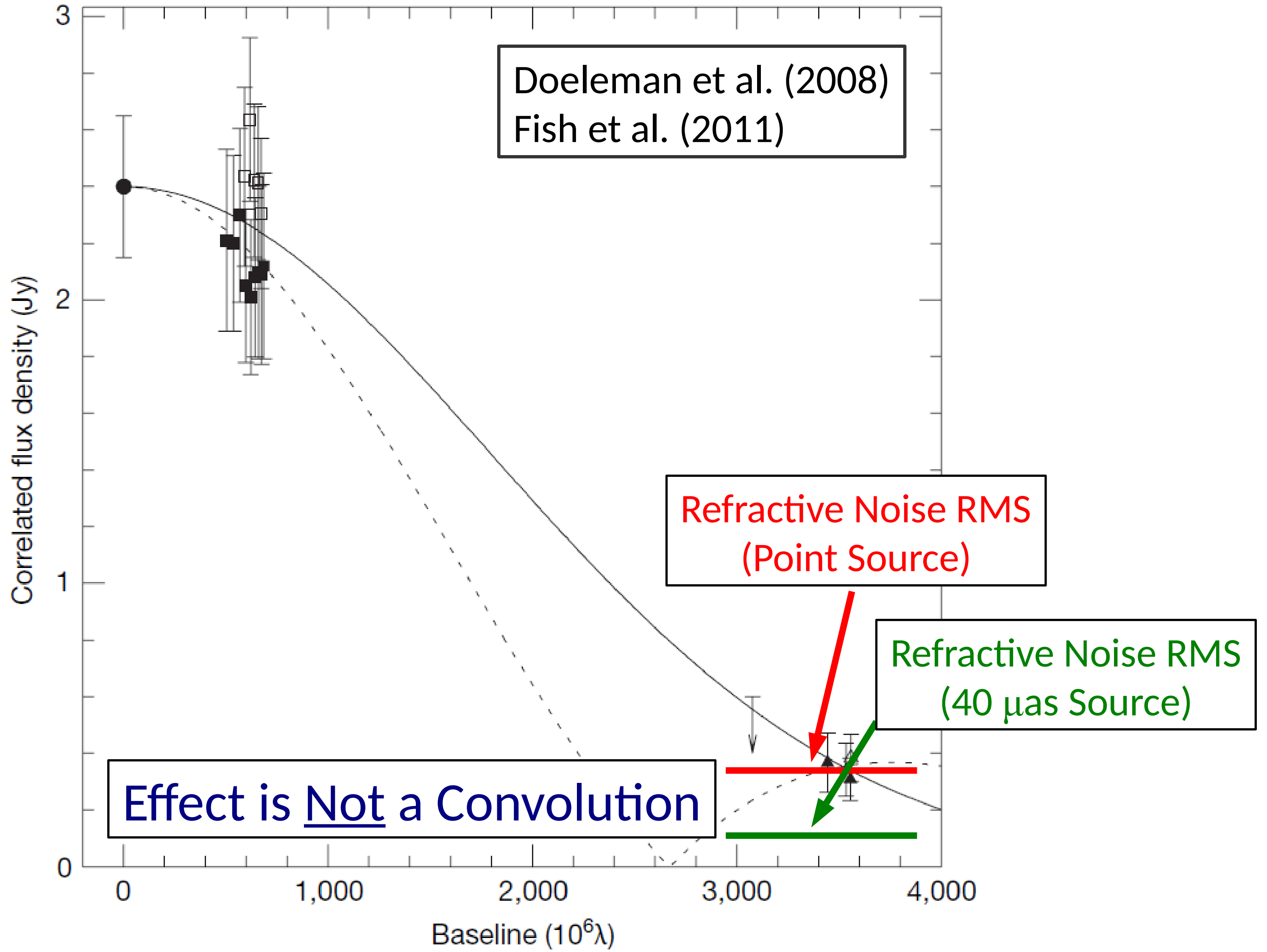


Notice:

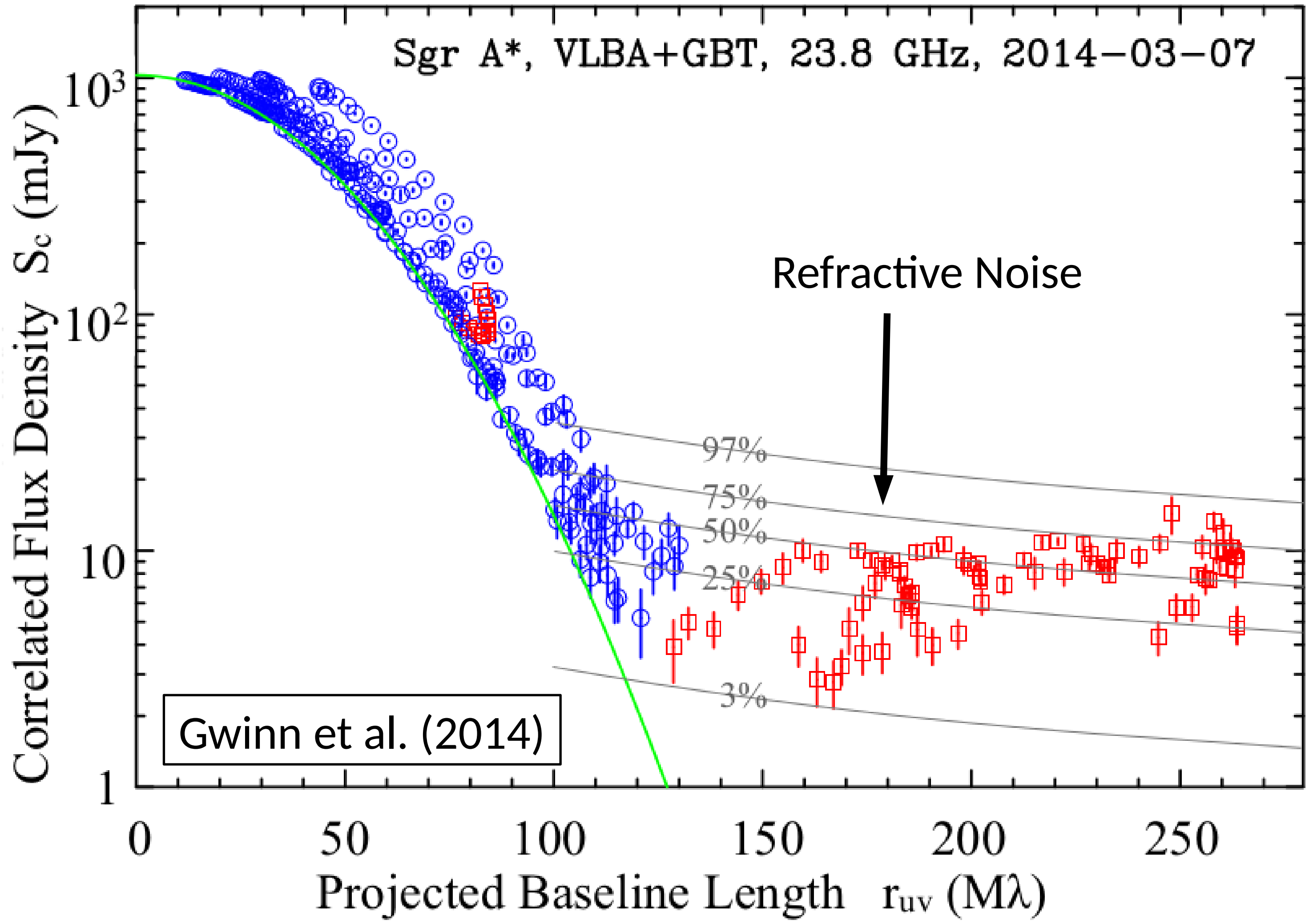
For a point source, the fractional refractive noise is higher at 0.87 mm
But, the same source size quenches the noise more at 0.87 mm

Johnson & Gwinn (2015)

Sgr A* with 1.3-mm VLBI



Refractive Substructure at 1.3 cm



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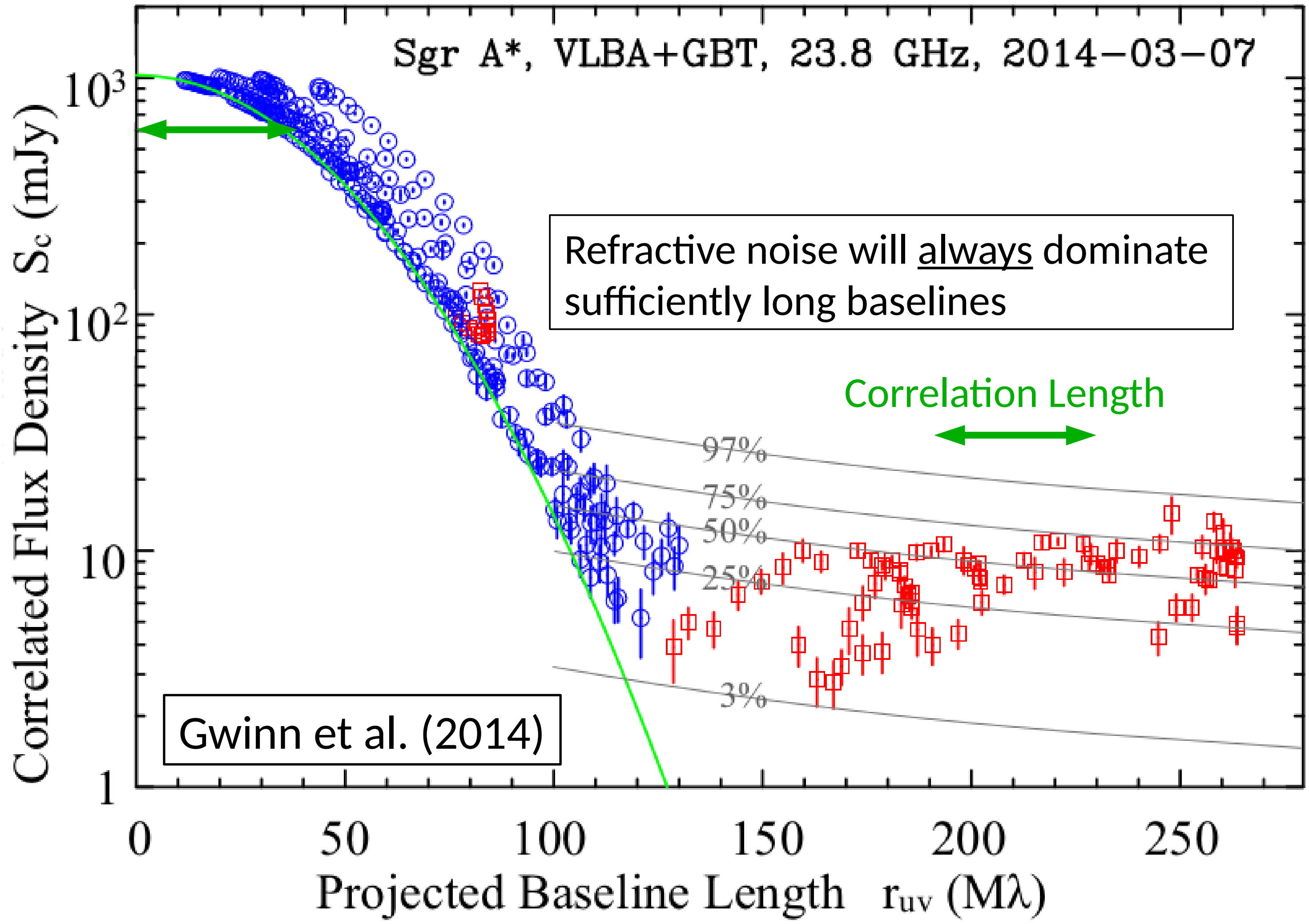
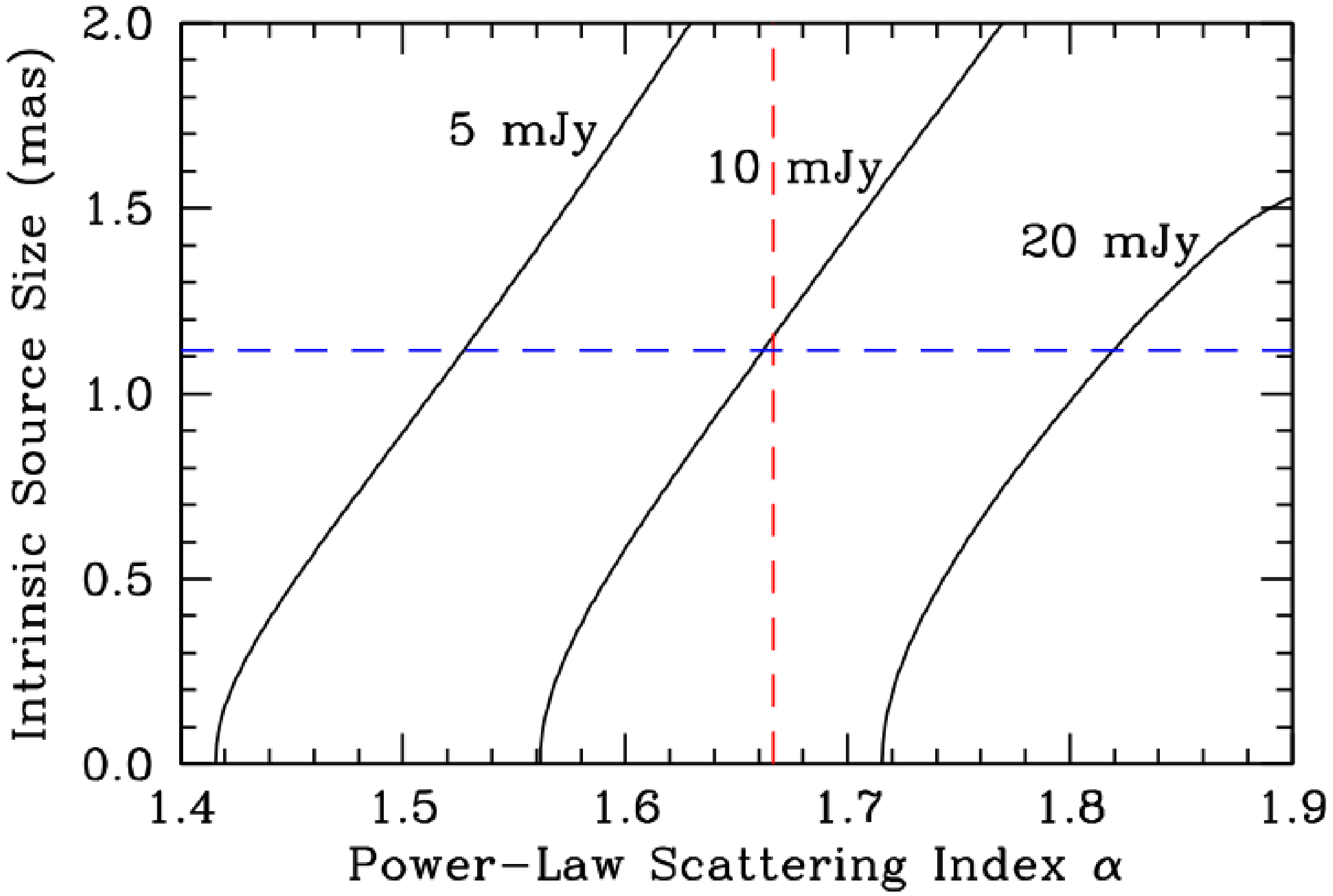
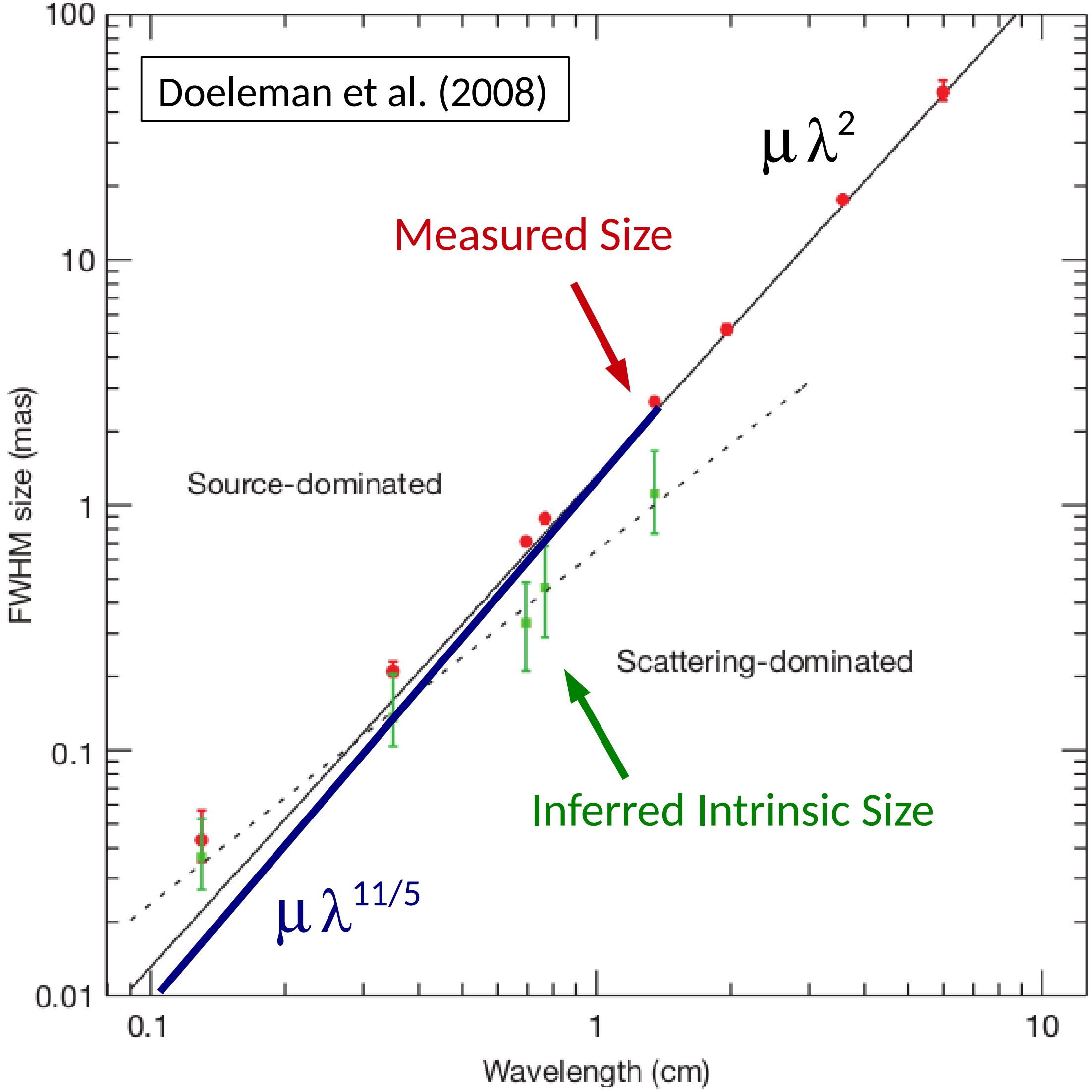


Refractive Substructure at 1.3 cm



Gwinn et al. (2014)

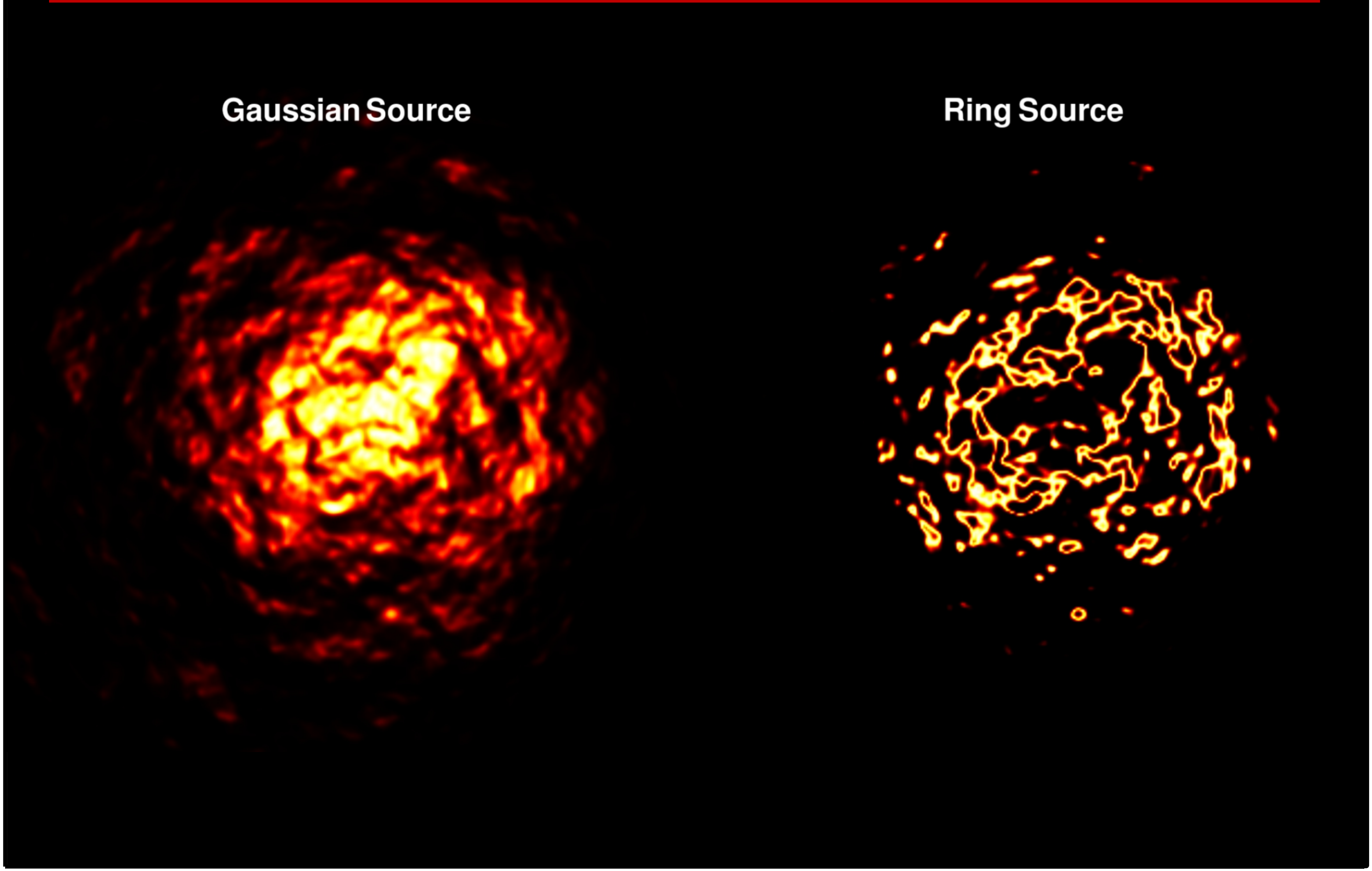
A Shallow Spectrum?



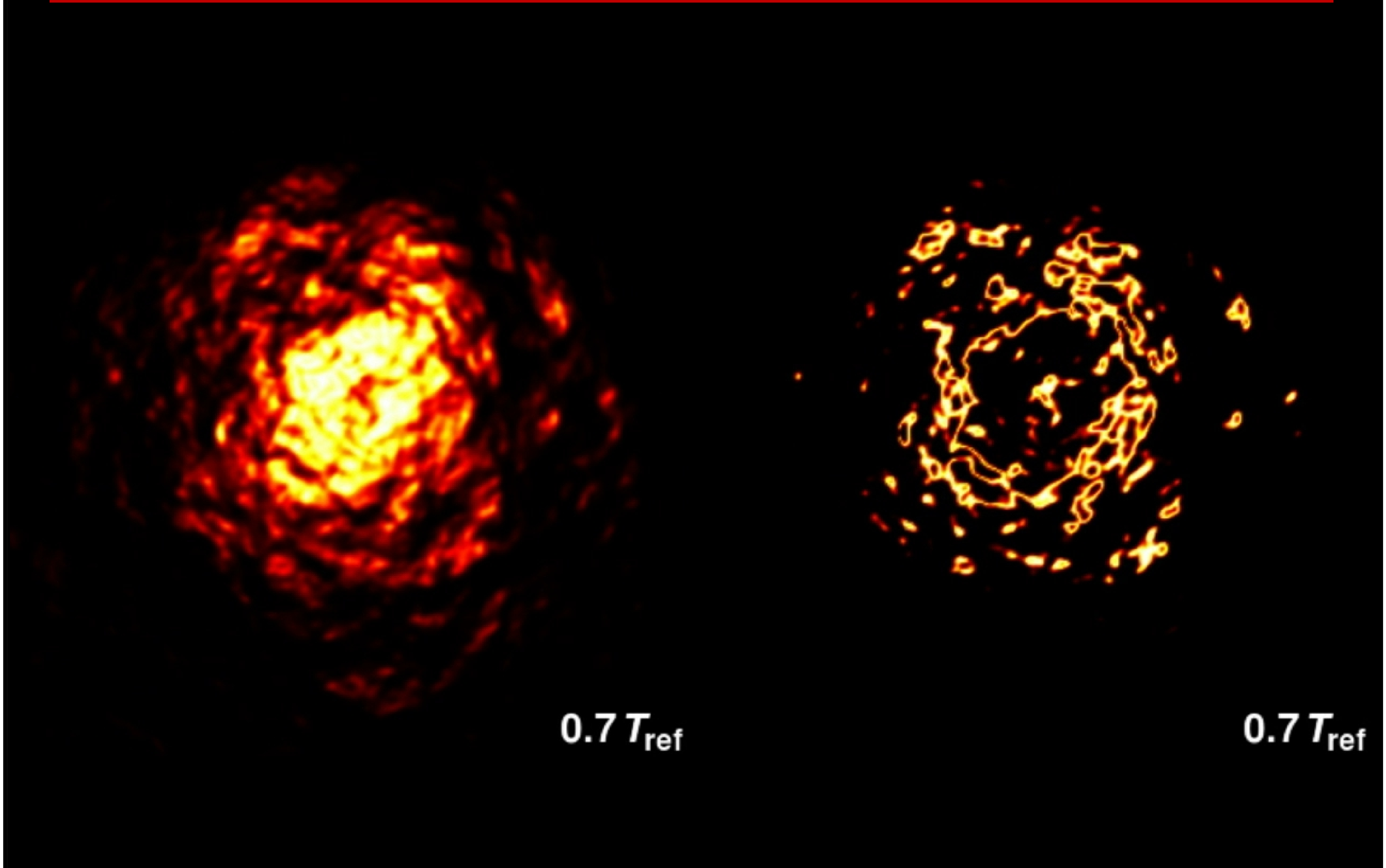
Shallow Spectrum
= Weaker Scattering

Important for deconvolution, especially on long baselines!

Subimages



Subimages



Summary

Scattering is important to understand and is still providing surprises
Scattering is not an afterthought for high-frequency VLBI

The dominant effect is blurring

- Invertible
- Equivalent to amplified noise (if the kernel is known)

The sub-dominant effect is substructure

- Variations distort single-epoch images (including the photon ring)
- $\lesssim$ 100 mJy noise seems a likely fundamental limit

The paradox:

- On long timescales, scattering smears things out. On short timescales, scattering introduces substructure.
- At shorter wavelengths: weaker blurring but stronger substructure

Topics for Discussion

We can now simulate the scattering for arbitrary images. To move forward requires an active interface between theory, simulations, and observations.

Major points for discussion:

1. Is the scattering kernel known?

2. Is the scattering really thin-screen?
   Where is the screen? What are its properties?

3. What mitigation techniques are possible for refractive effects?
   Are blind deconvolution techniques applicable?

4. What is the role of the magnetar?

5. Same framework as atmospheric scattering! Add to simulations?