Effects of Interstellar Scattering on VLBI Observations

Pulsar Working Group
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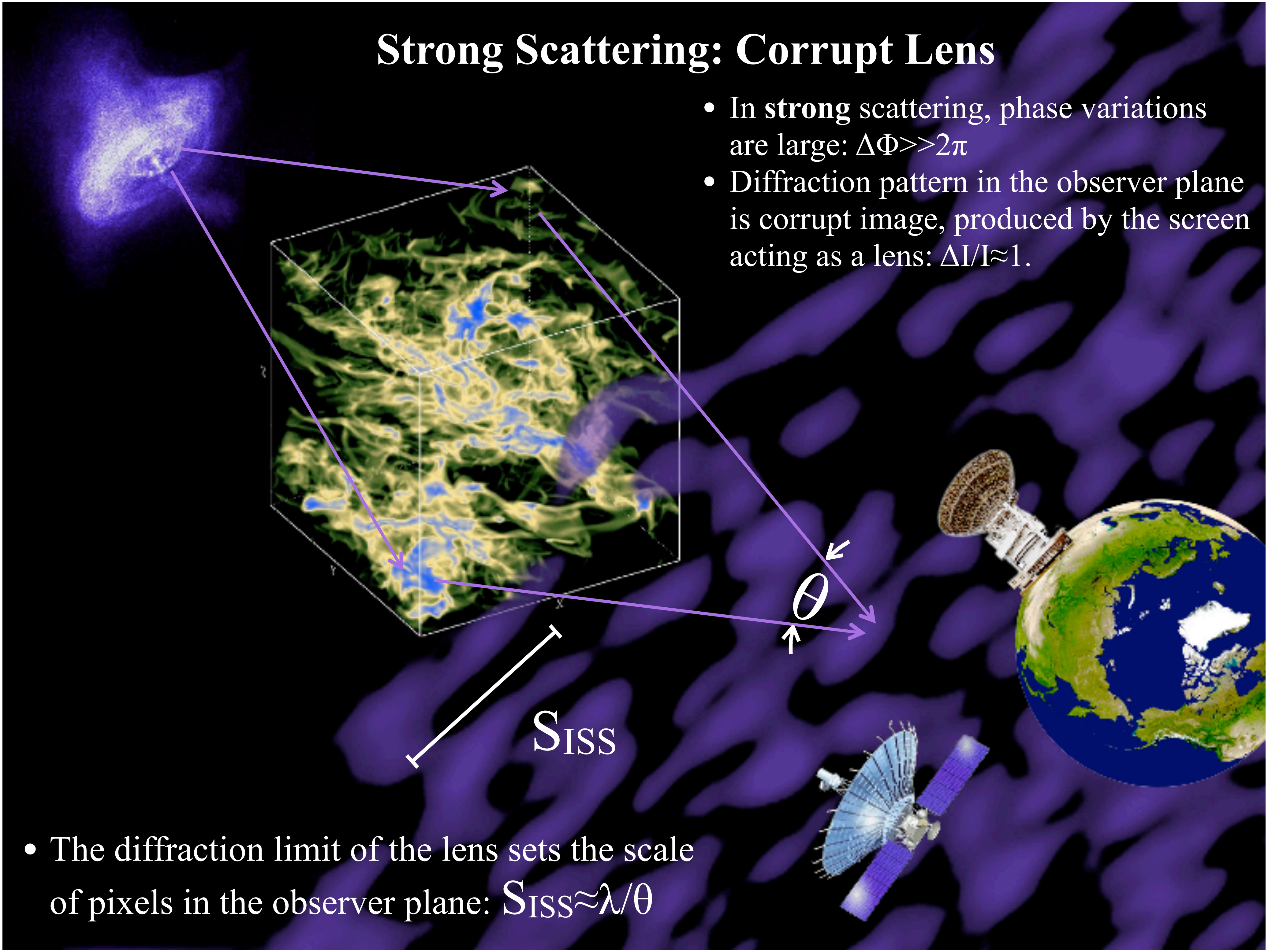
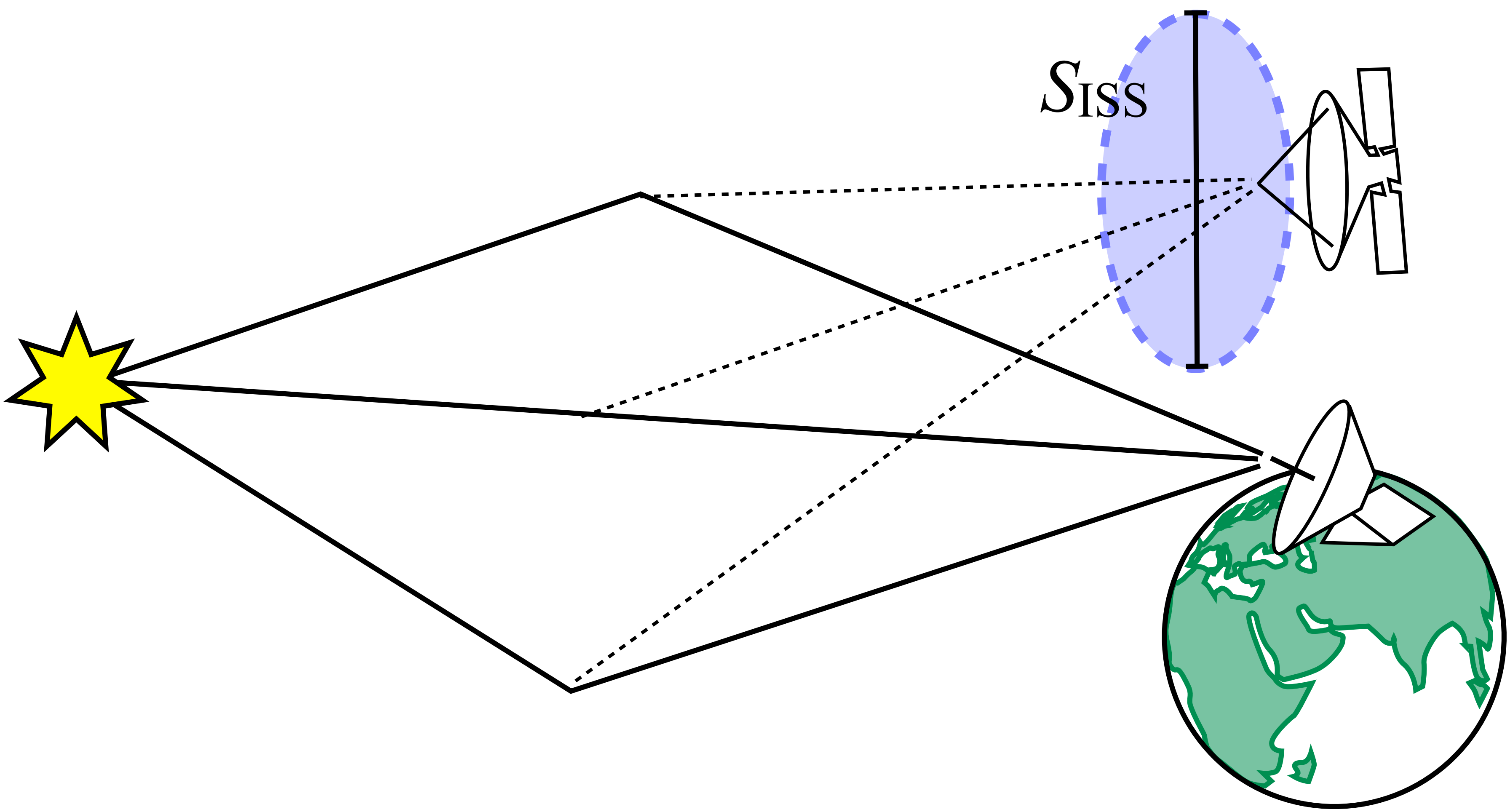
- The Simplest Picture of Strong Scattering
  - ✳Observations
  - ✳Kirchoff Integral
  - ✳Distributions
- Visibility on Long Baselines: Substructure in the Scattering Disk
  - ✳Observations
  - ✳Theoretical Predictions
- Substructure in Scattering Disks and Source Structure


Strong Scattering: Corrupt Lens
• In strong scattering, phase variations are large: ΔΦ>>2π
• Diffraction pattern in the observer plane is corrupt image, produced by the screen acting as a lens: ΔI/I≈1.
θ
SISS
• The diffraction limit of the lens sets the scale of pixels in the observer plane: SISS≈λ/θ

Strong Scattering: Corrupt Lens

For most pulsars: S_{ISS}≈Earth diameter

RadioAstron affords the first opportunity to compare scattering between 2 different pixels (resolution elements).



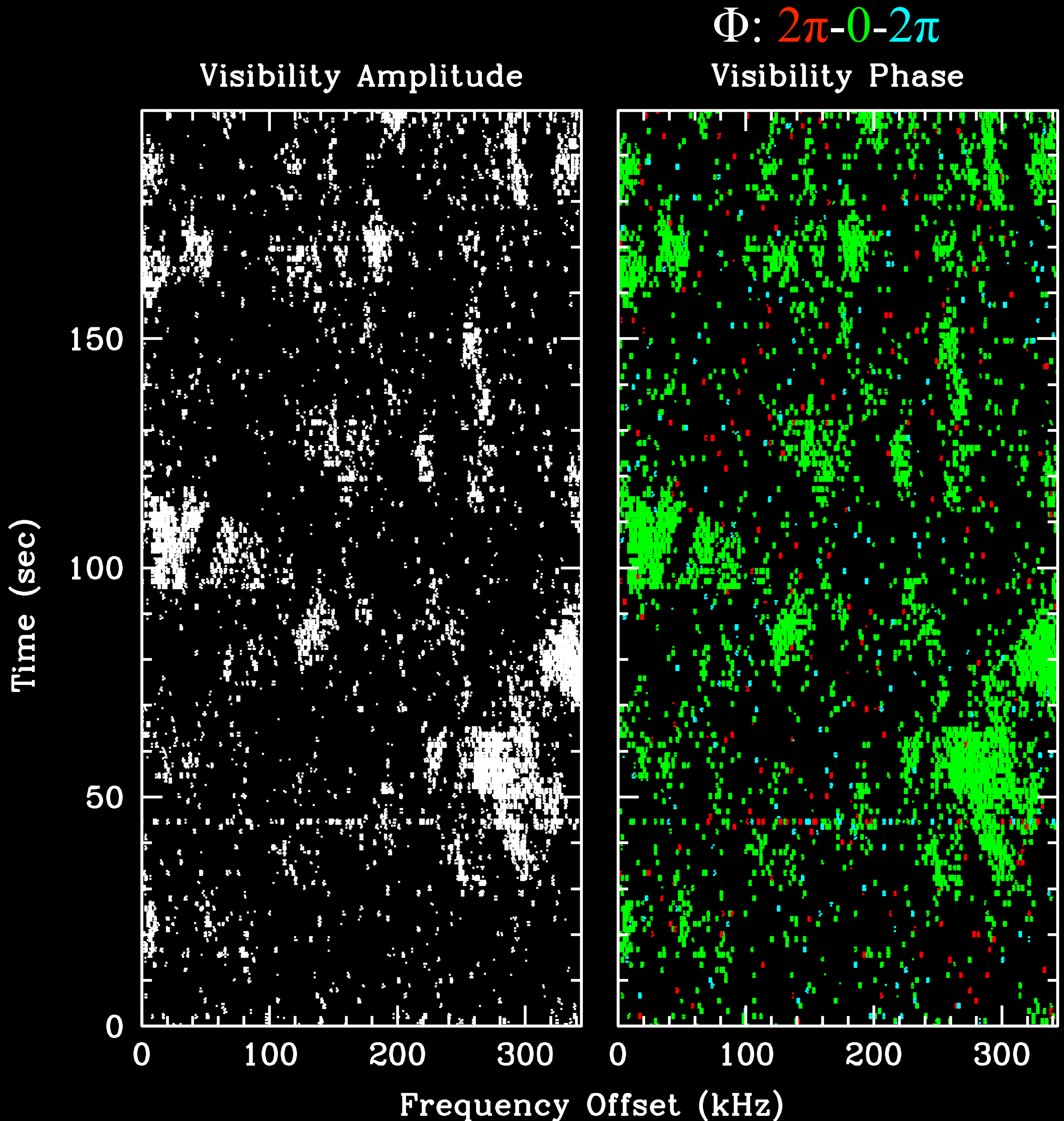
Vela Pulsar

1. Objective: Understand visibility on long baselines of this strong, heavily-scattered pulsar.

2. Observations: Space-earth and Earth-earth observations at 3 epochs, 2 epochs RA detection.

Vela

<u>Short baseline:</u>
Tid-Parkes.
Amplitude variations:
$\Delta I/I = 100\%$
Phase variations:
$\Delta\Phi \approx 0$



Vela

<u>Long baseline:</u>
RadioAstron-Tid
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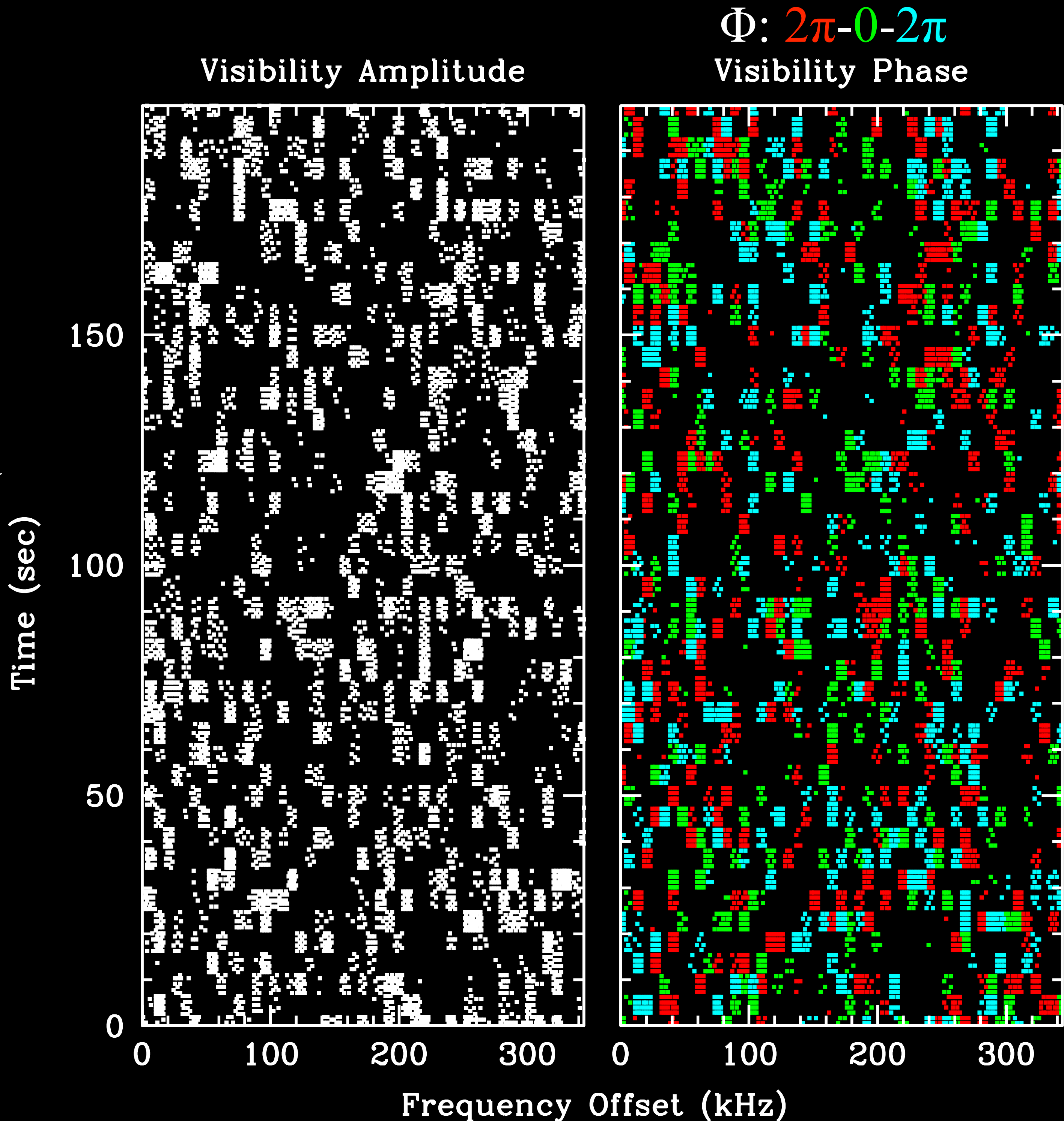


The Simplest Model for Scattering:

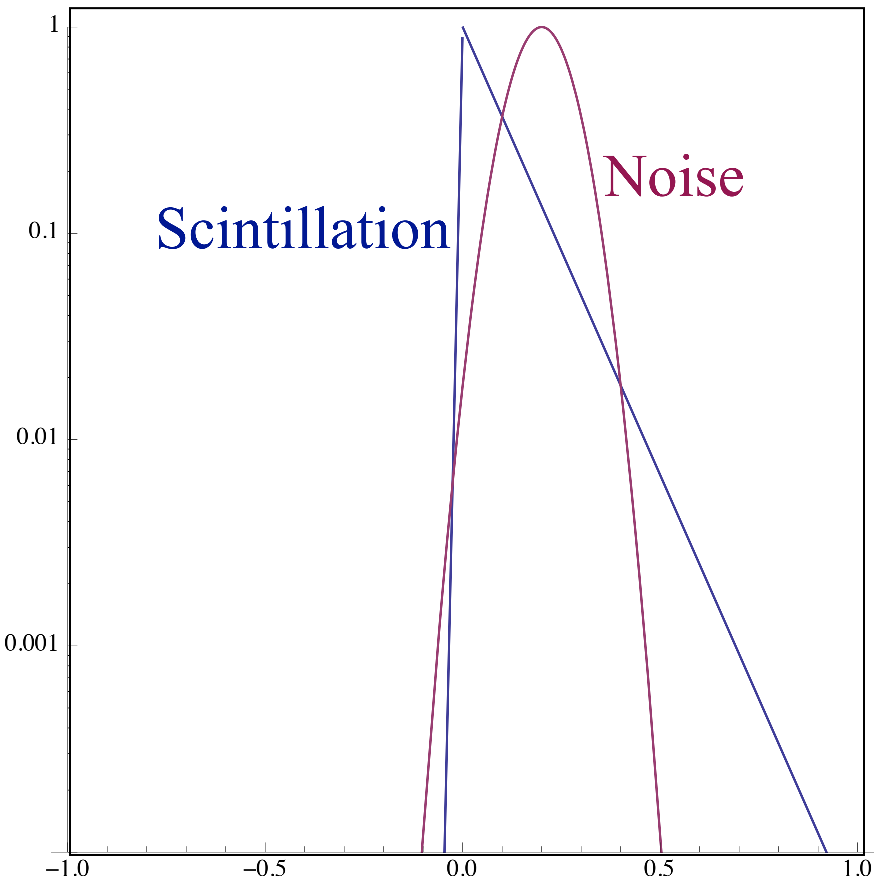
- Phase variations are not correlated in frequency or time.
- Amplitude variations are also uncorrelated.
- Visibility=1 on very short baselines, declines with baseline length, and reaches V=0 when phase variations→2π

Is the Simplest Model Enough? And What About AGN? Are They Visible on Long Baselines Despite Scattering?

Distribution for Short Baseline

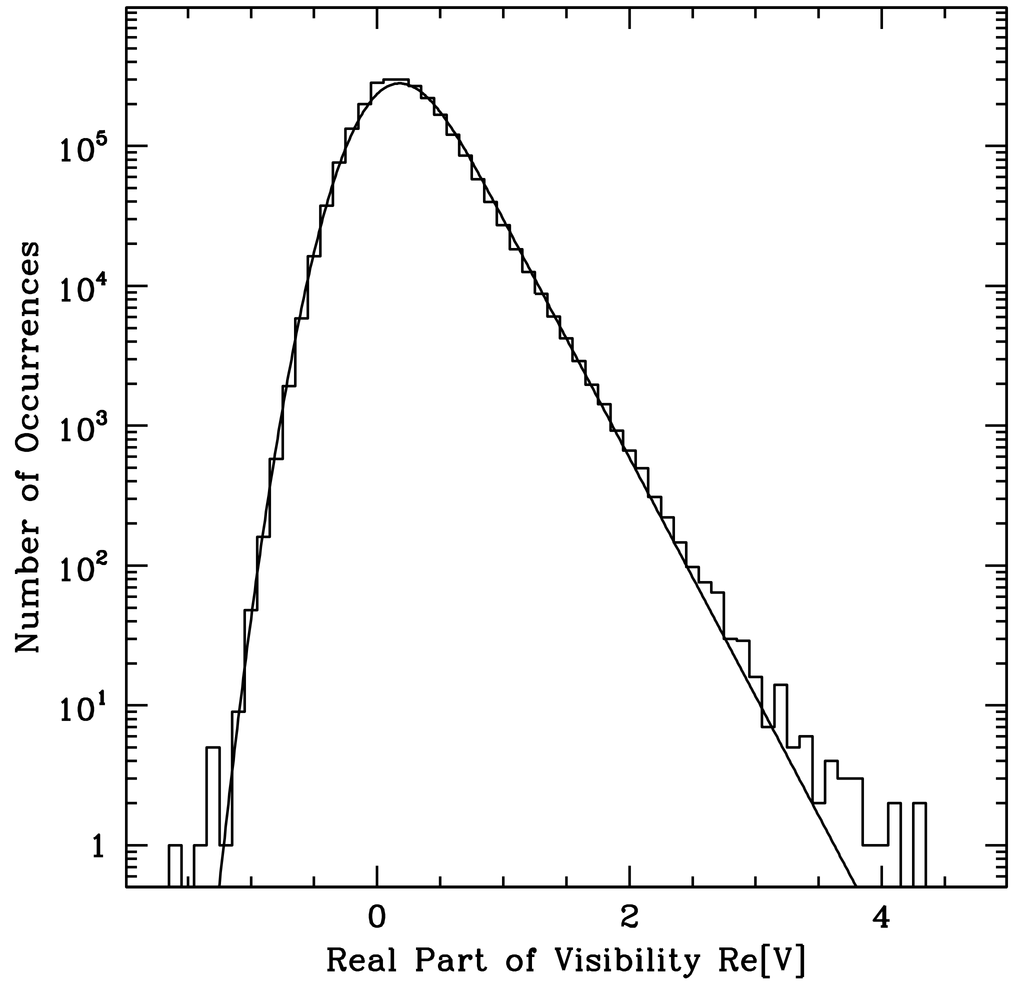
P(V) for 2 very close antennas is an exponential distribution, along the real axis in the complex plane.

$$P(V) = \frac{1}{I_0} \exp\left(-\frac{V}{I_0} \right), \quad V \geq 0$$



Observed distribution is the convolution of scintillation and noise

Vela Pulsar: Parkes-Tidbinbilla:
Baseline=Δp=300 km

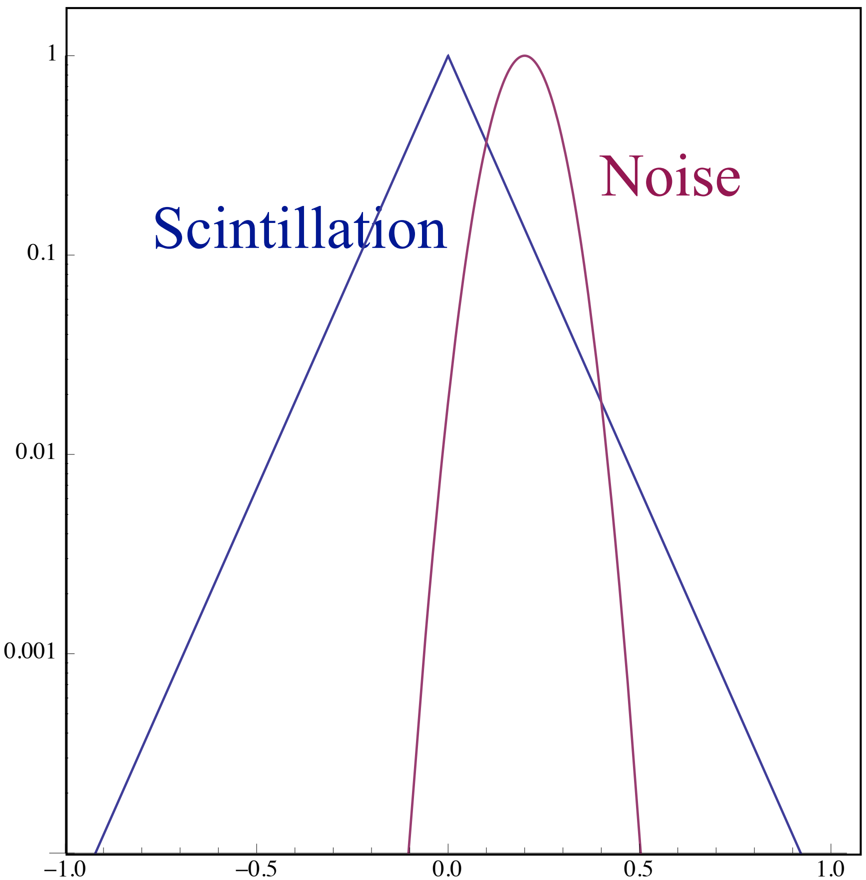


Distribution for Long Baseline

If 2 antennas are far apart, electric fields at the 2 points are uncorrelated. In this case, real part of visibility is drawn from a 2-sided exponential distribution.

$$P(V) = \frac{1}{I_0} \exp\left(-\frac{|V|}{I_0} \right)$$

Vela Pulsar: Parkes-RadioAstron:
Baseline=Δp=110,000 km



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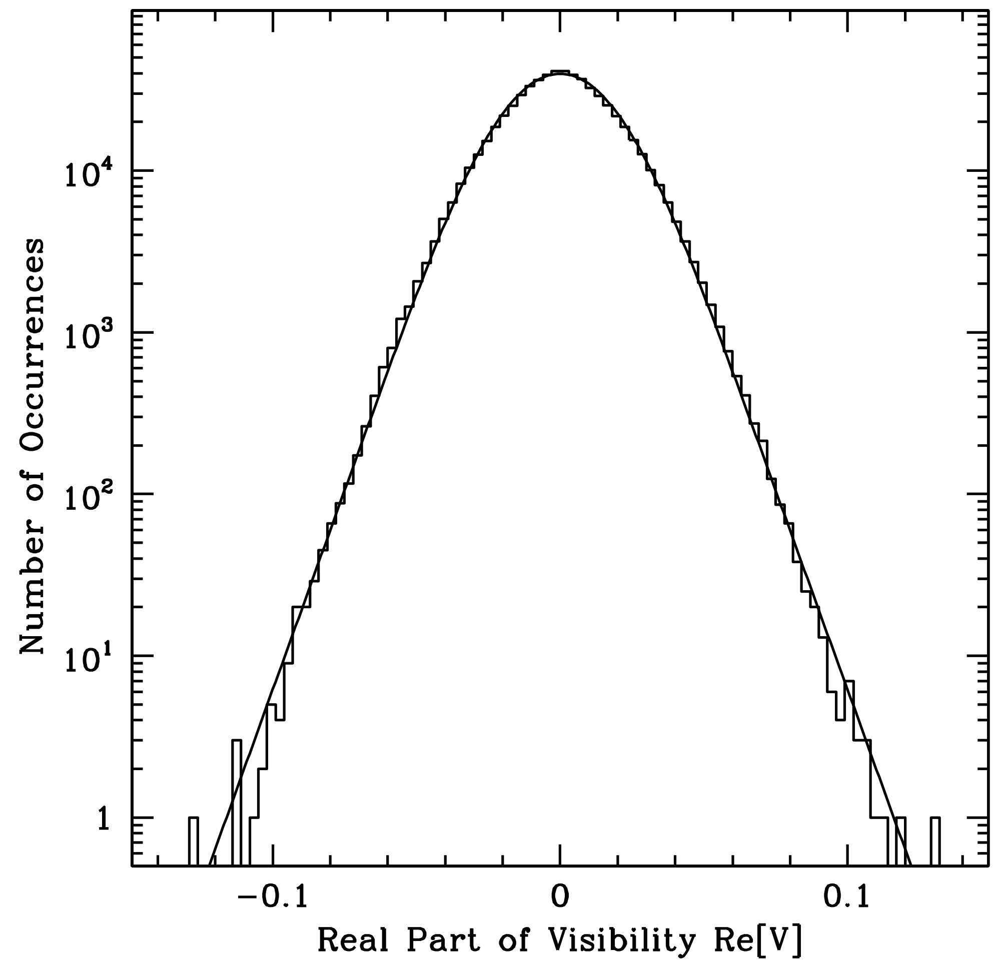
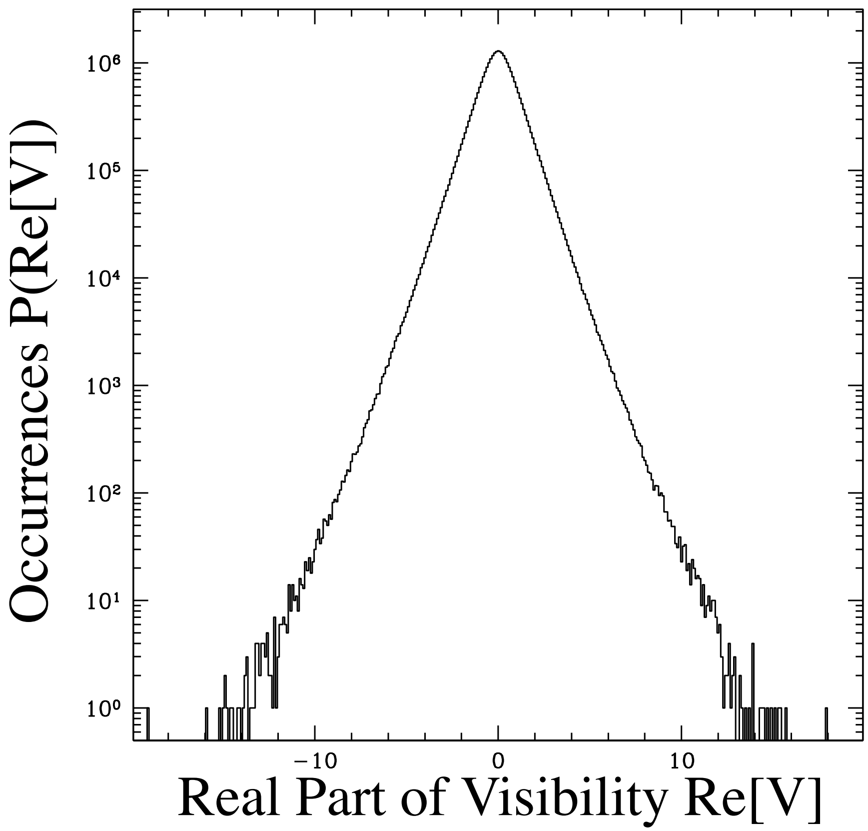
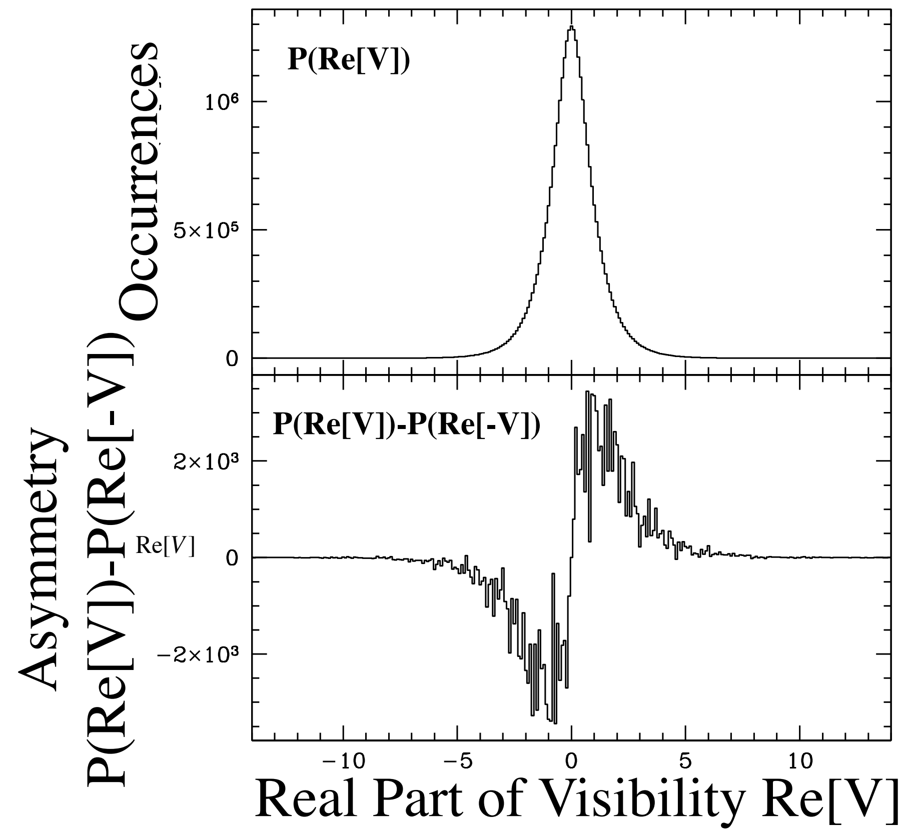


Vela Pulsar

Tidbinbilla-RadioAstron fringes show persistent fringes





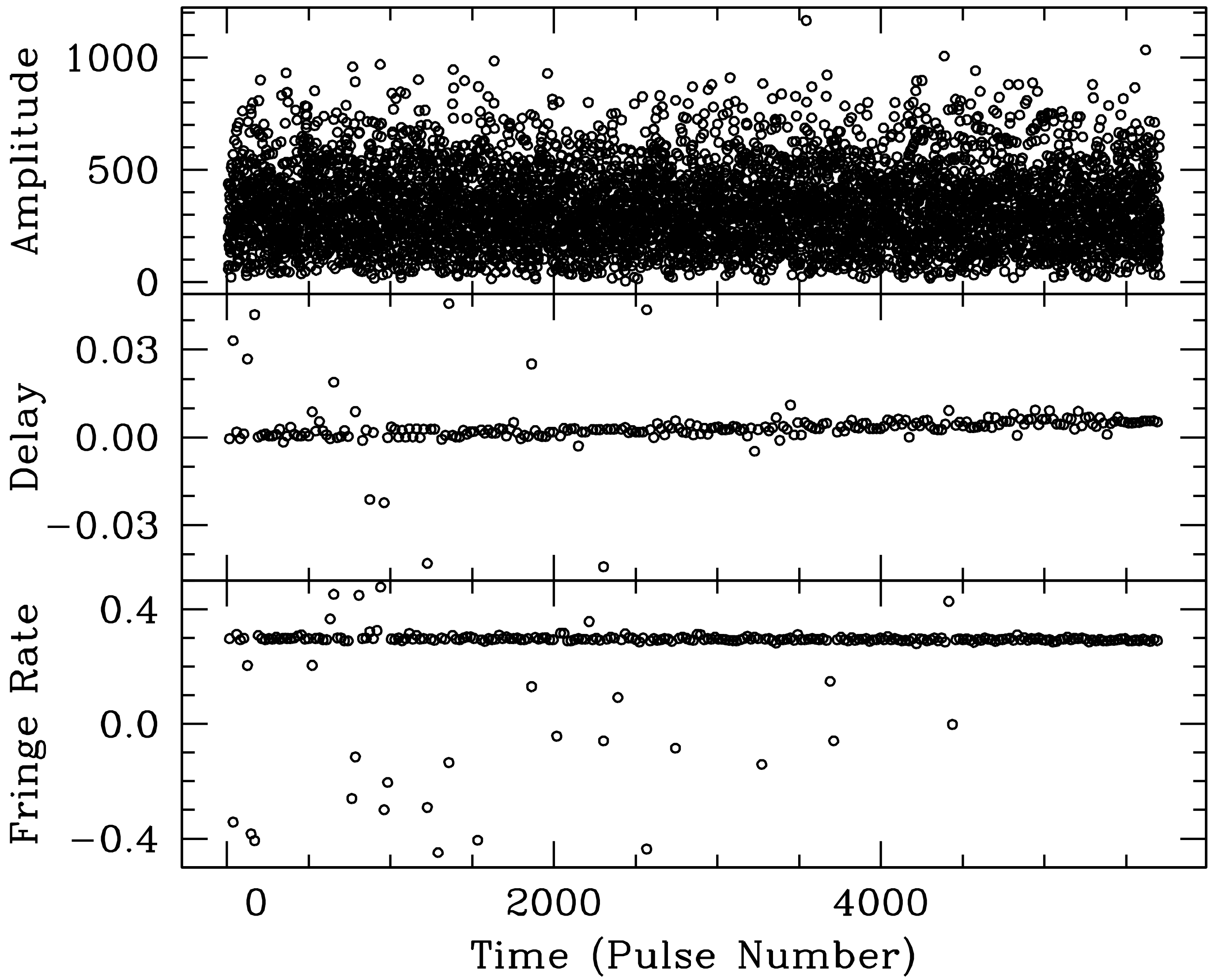
- We removed the best-fitting 4-parameter model (delay, delay rate, fringe rate, phase) from a span of 5700 pulses (500 sec).
- Visibilities of individual pulses follow the expected distribution:

$$P(\mathrm{Re}[V]) = (1/2s)\exp\left(-\left|\mathrm{Re}[V]/s\right|\right)$$

with a **1% asymmetry toward +Re[V]**.

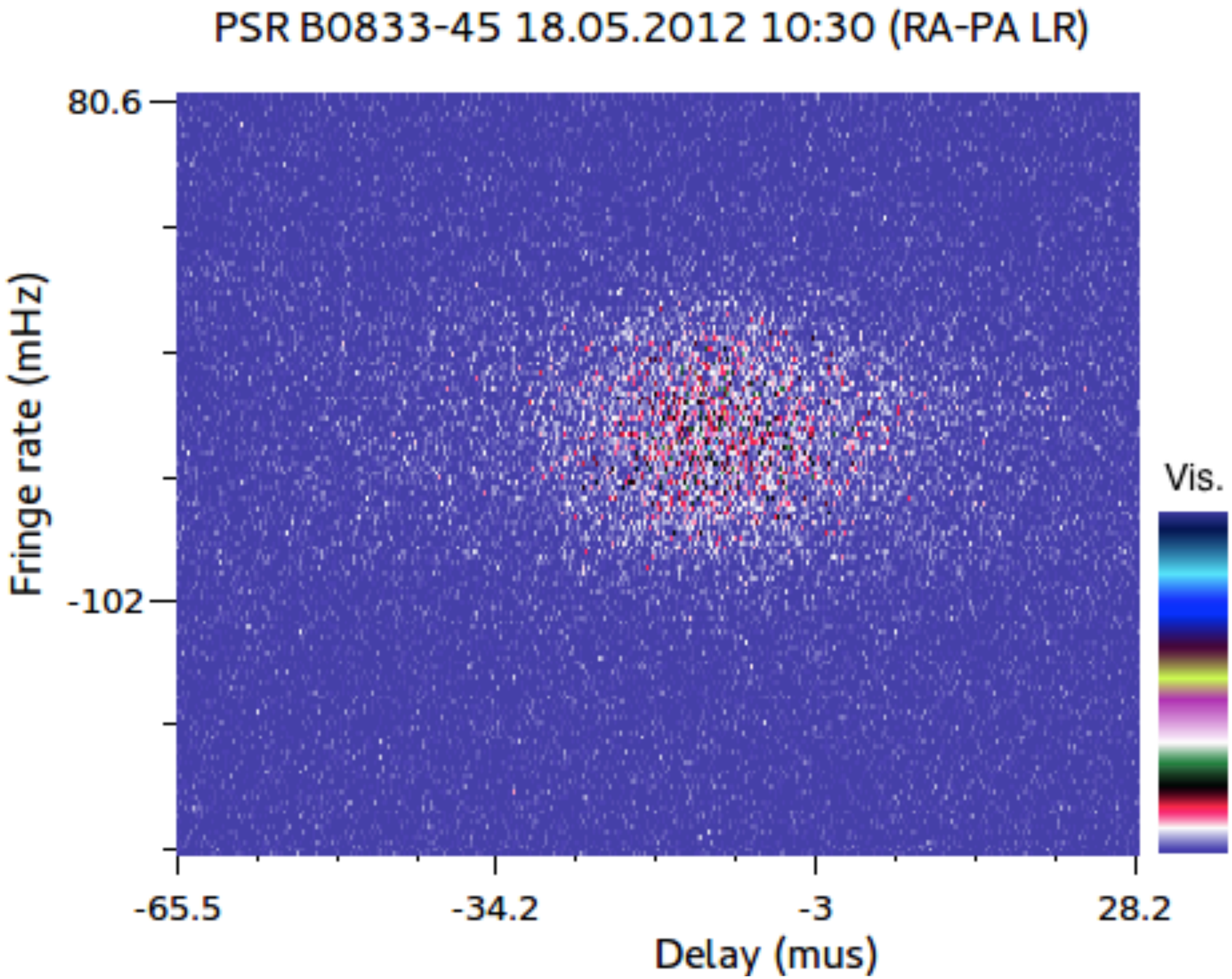
Vela

Fringes on the long RadioAstron-Tidbinbilla baseline (110,000 km)



Vela

A correlation function displays “fractal” structure of the fringes.



Vela

Vela Pulsar

1. Objective: Understand visibility on long baselines of this strong, heavily-scattered pulsar.

2. Observations: Space-earth and Earth-earth observations at 3 epochs, 2 epochs RA detection.

3. Results: Behavior on Earth baselines matches a simple model. On long baselines, we detect fringes in the face of large phase variations. This does not match simple models.

4. Status: Analysis in progress.

B0329+54

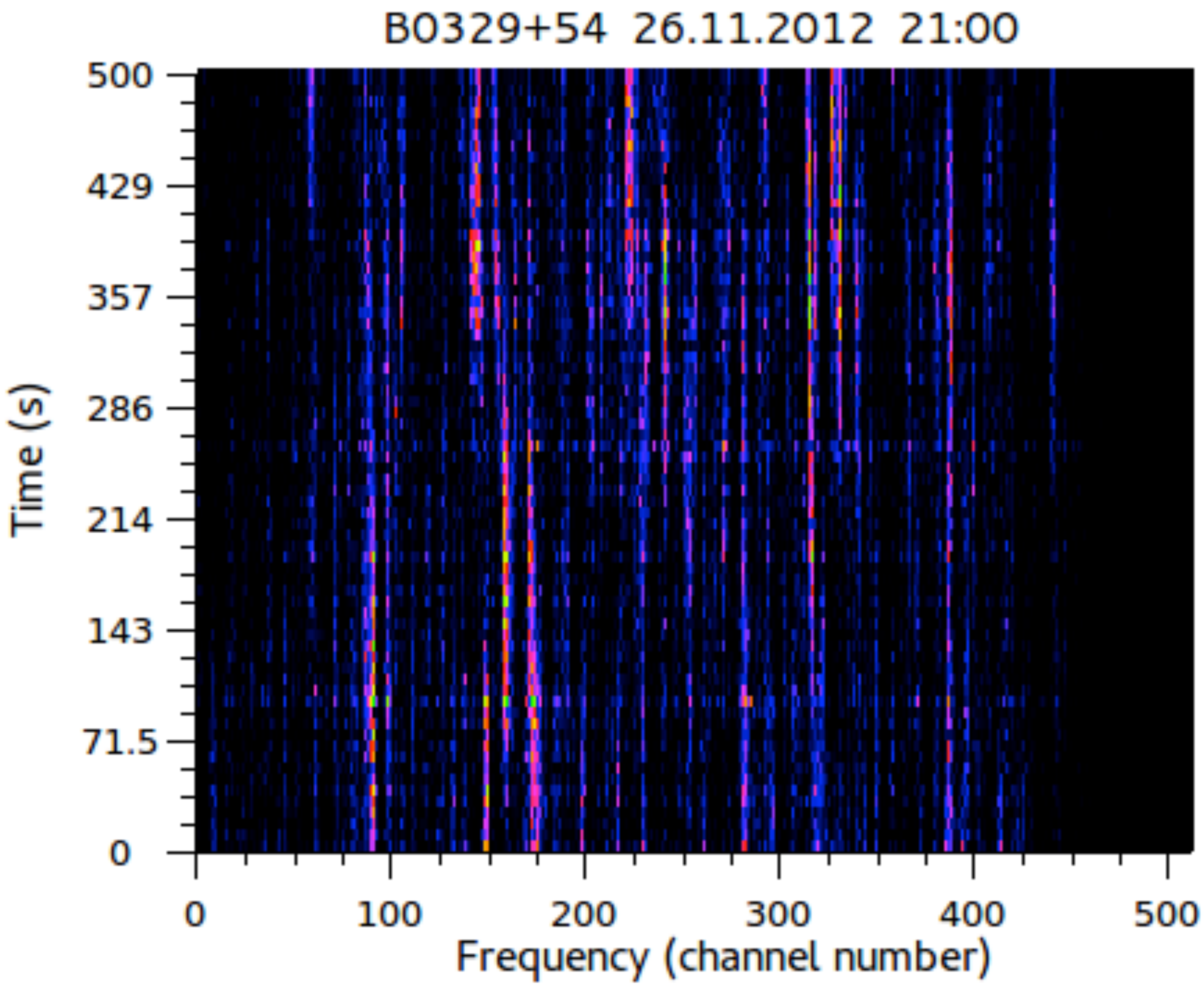
Pulsar B0329+54

1. Objective: Understand visibility on long baselines by studying the transition from short earth-earth to long space-earth baselines.
2. Program: Study visibility on a wide range of baselines of this strong, moderately-scattered pulsar.
3. Observations: Several observations with sensitive long and short baselines.

B0329+54

For the strong nearby pulsar B0329+54, the dynamic cross-spectrum between GBT and RadioAstron shows strong amplitude variations from scintillation.

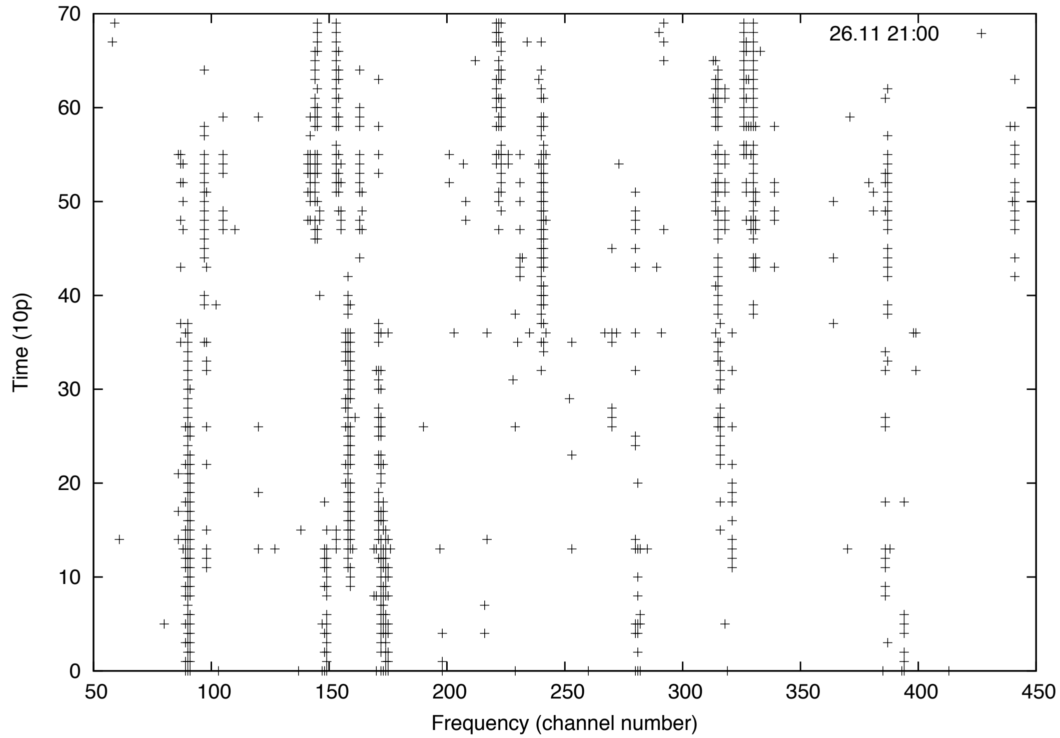
Each line=10-pulse average
Scaled for amplitude variations of pulses



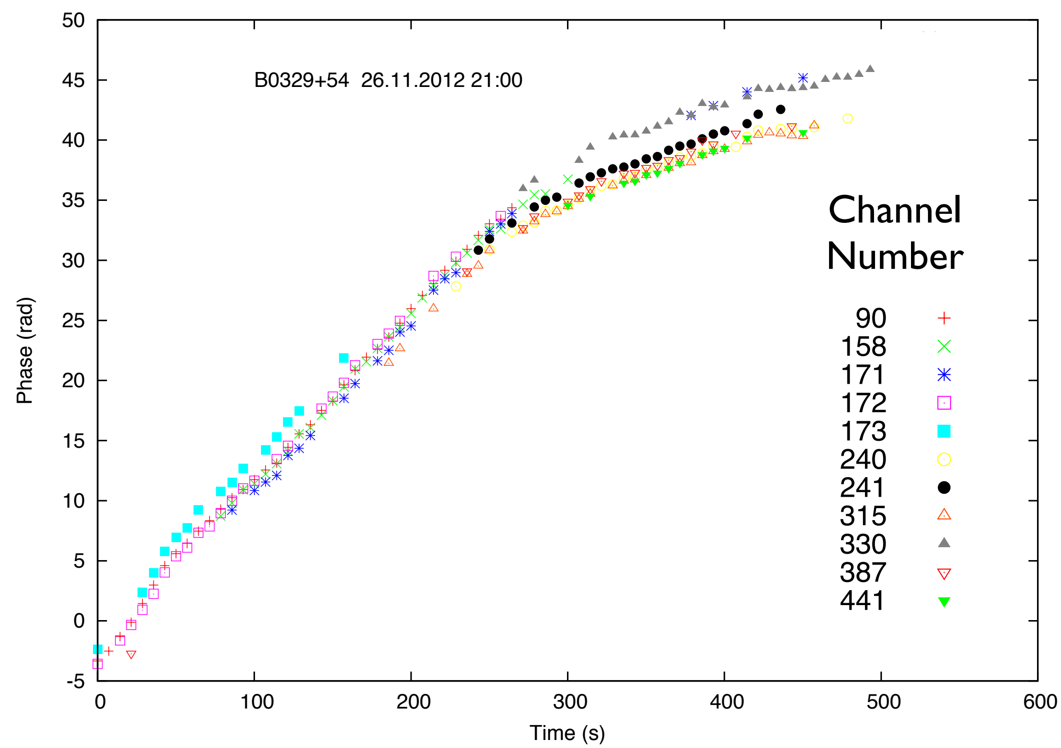
326 MHz

B0329+54

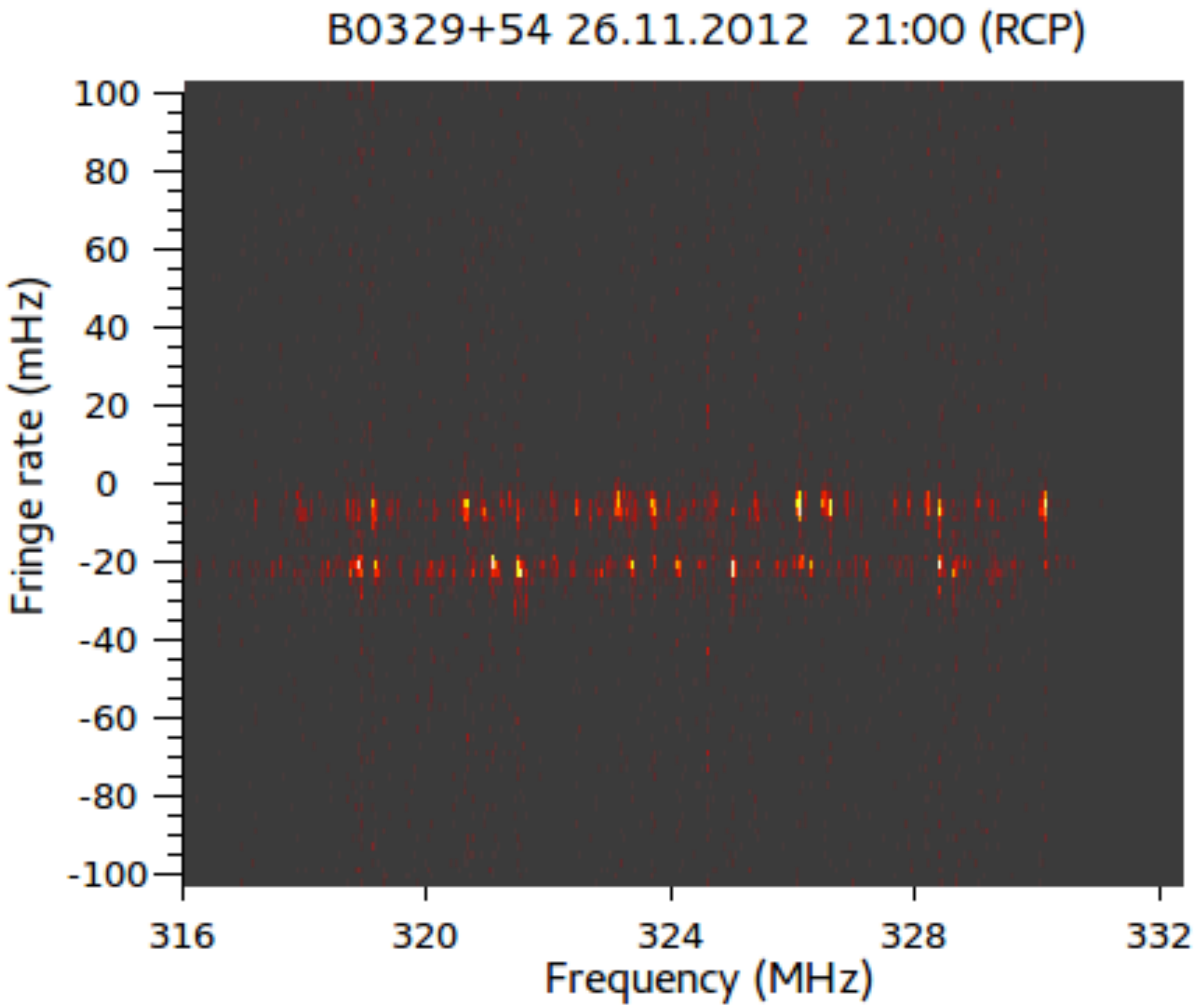
Selected strong scintillations in the dynamic spectrum provide accurate interferometer phases.



Phases vary with time, and across the spectrum. Phase variations over the source are less than 2π with frequency, for RadioAstron-GBT baseline at medium projection.

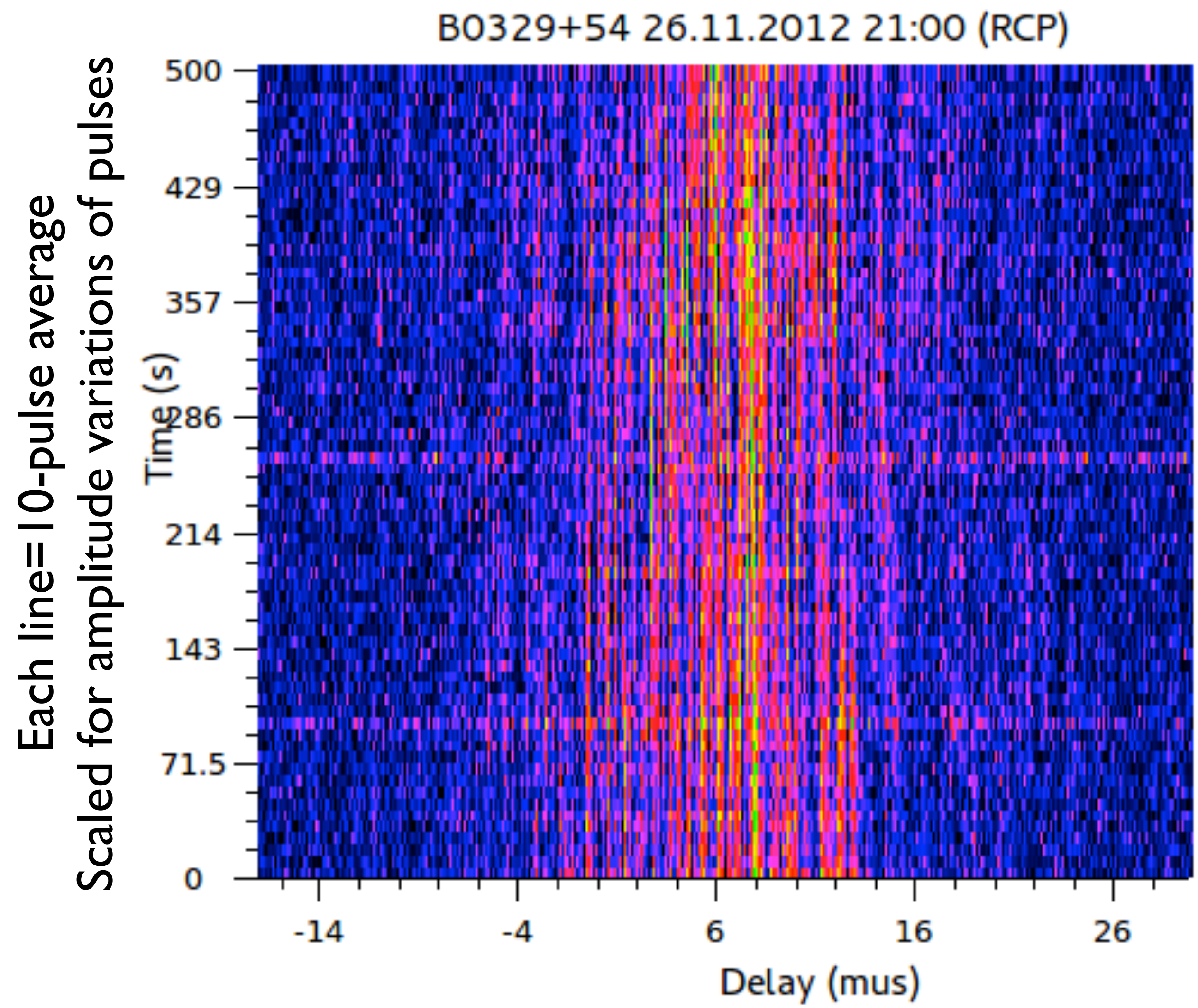


The variations of phase with time split the fringes in the delay/fringe-rate domain.
This splitting decreases with increasing baseline length.



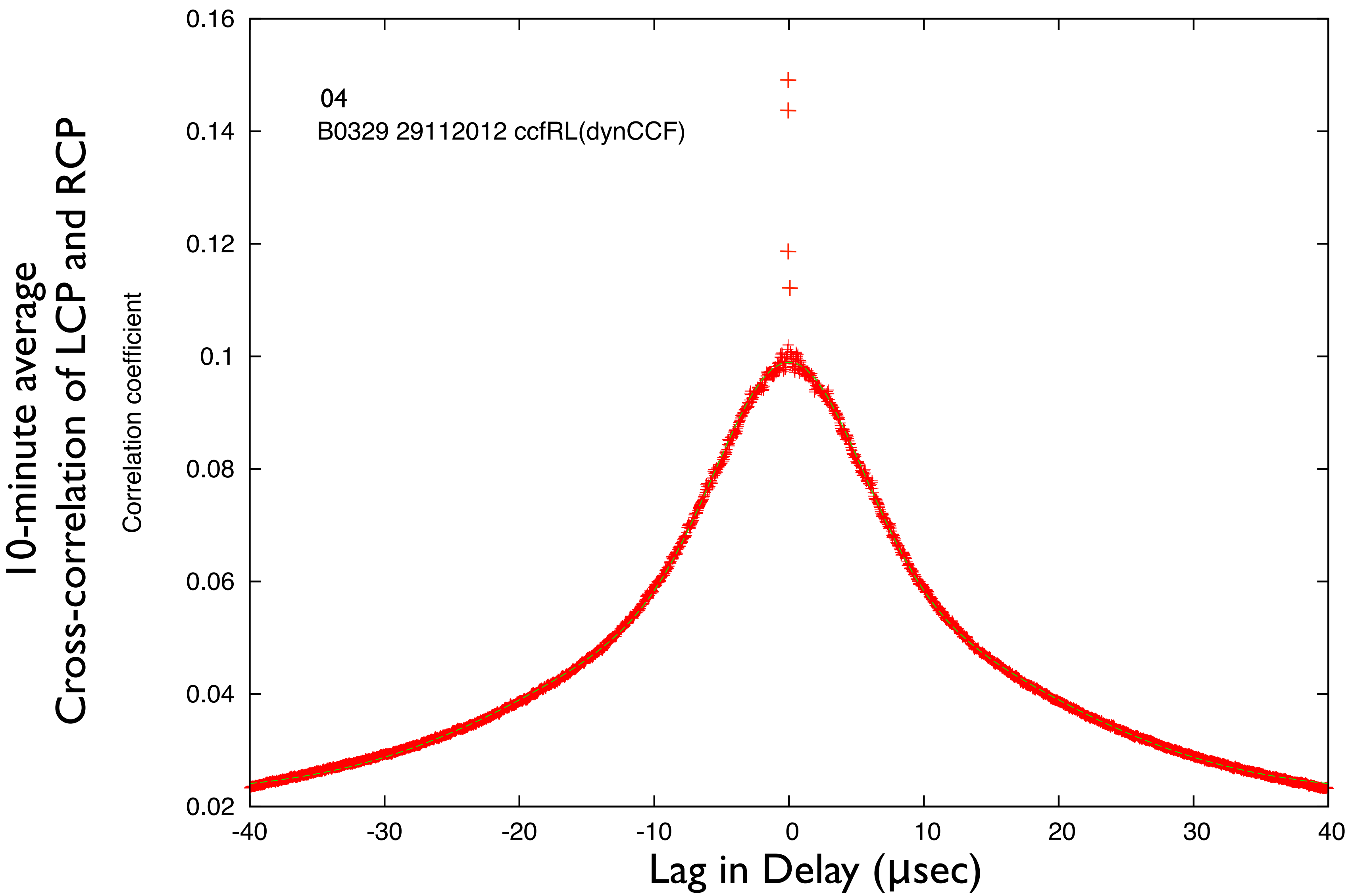
B0329+54

Autocorrelation of the scintillation spectrum reveals rich structure over a range of delays, and strong correlation at one delay.



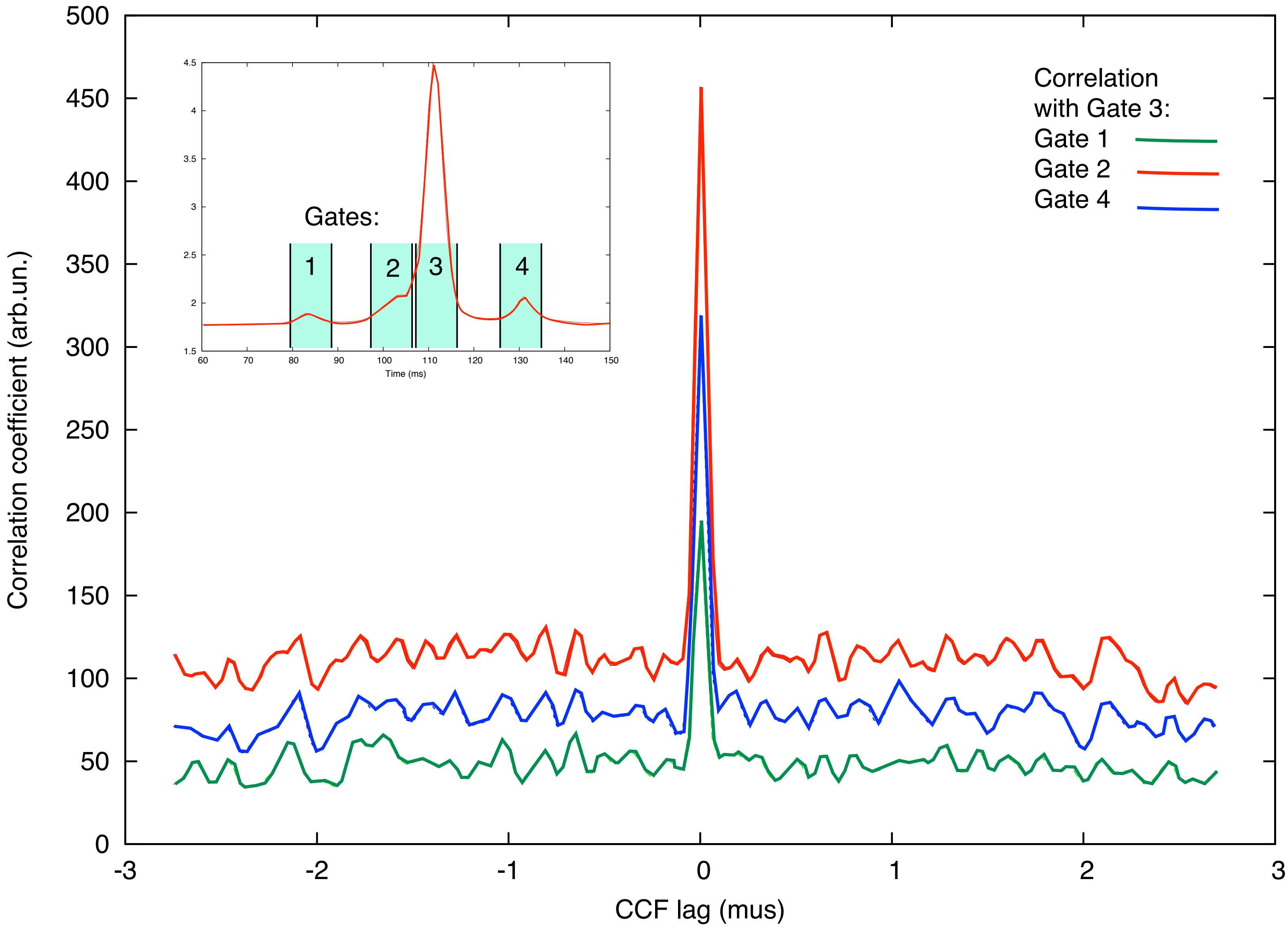
B0329+54

The correlation function, averaged in time, shows large-scale and very small-scale variation in delay.

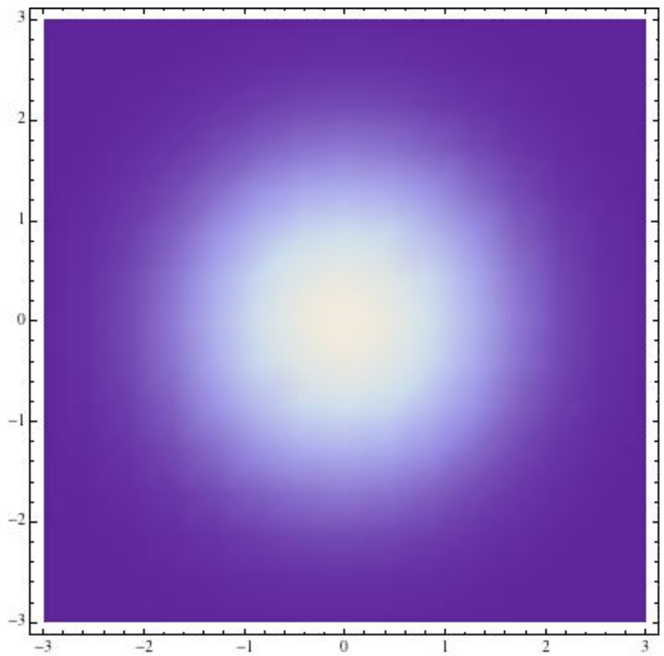


B0329+54

Correlation of the fine-scale structure between different pulse gates demonstrates that the narrow peak is not due to noise.

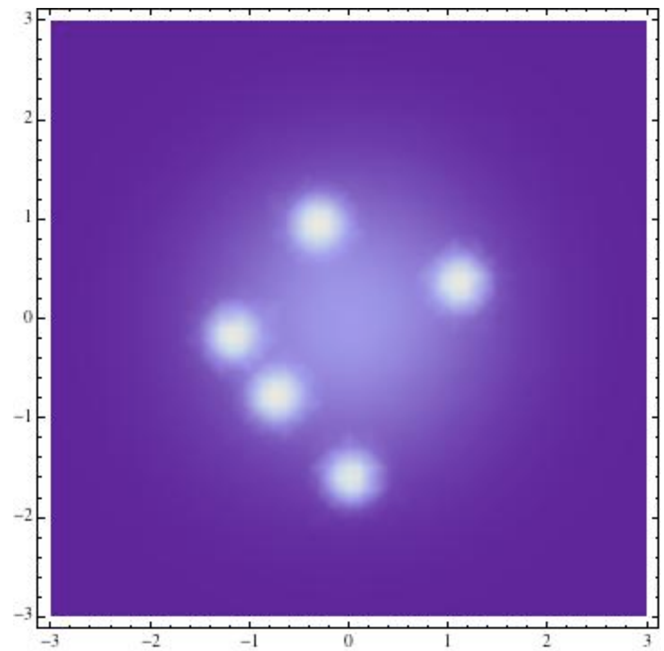


Large-scale correlations indicate small-scale structure within the scattering disk



View on the Sky

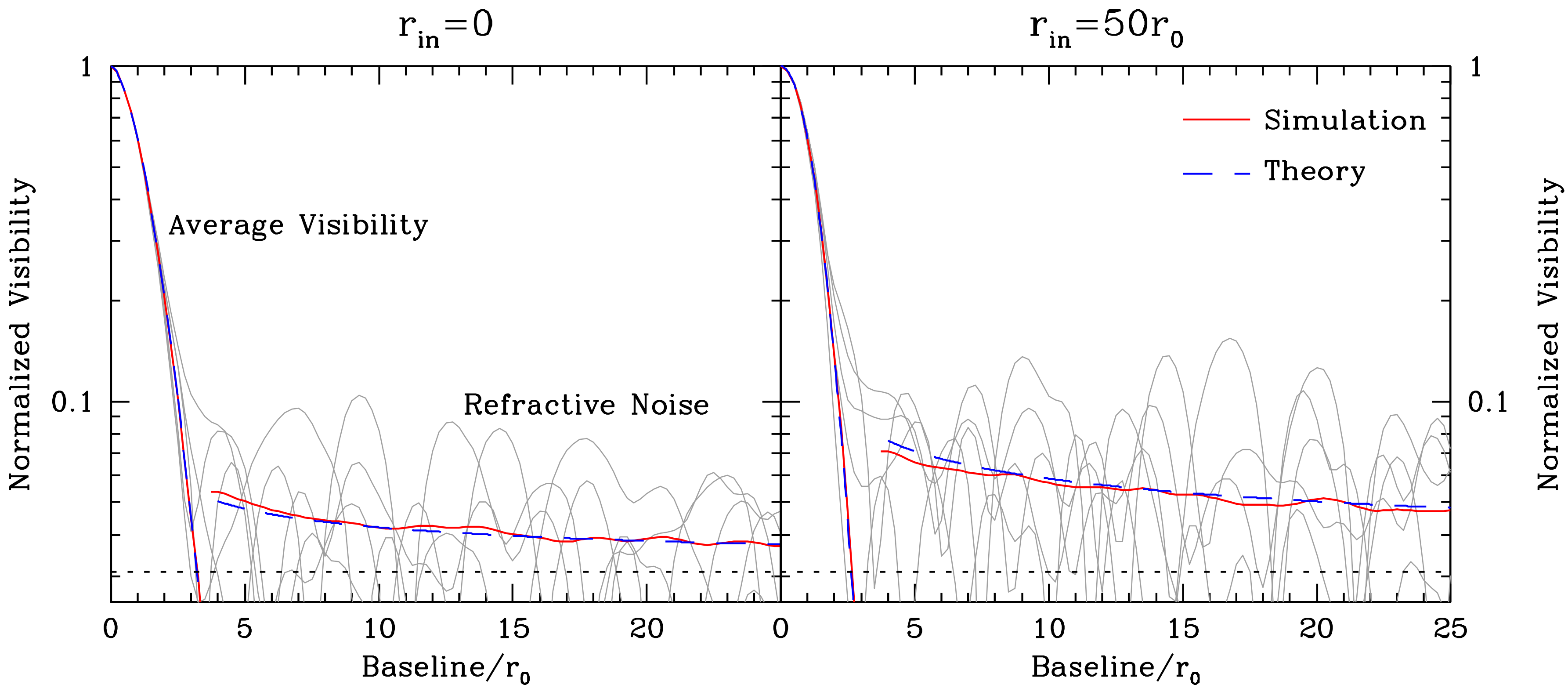
?



Correlations on long baselines indicate small-scale structure in the screen.

Such structure might arise from refraction by large-scale plasma fluctuations, or non-Gaussian statistics of scattering. A large "inner scale" of density fluctuations can enhance the effect.

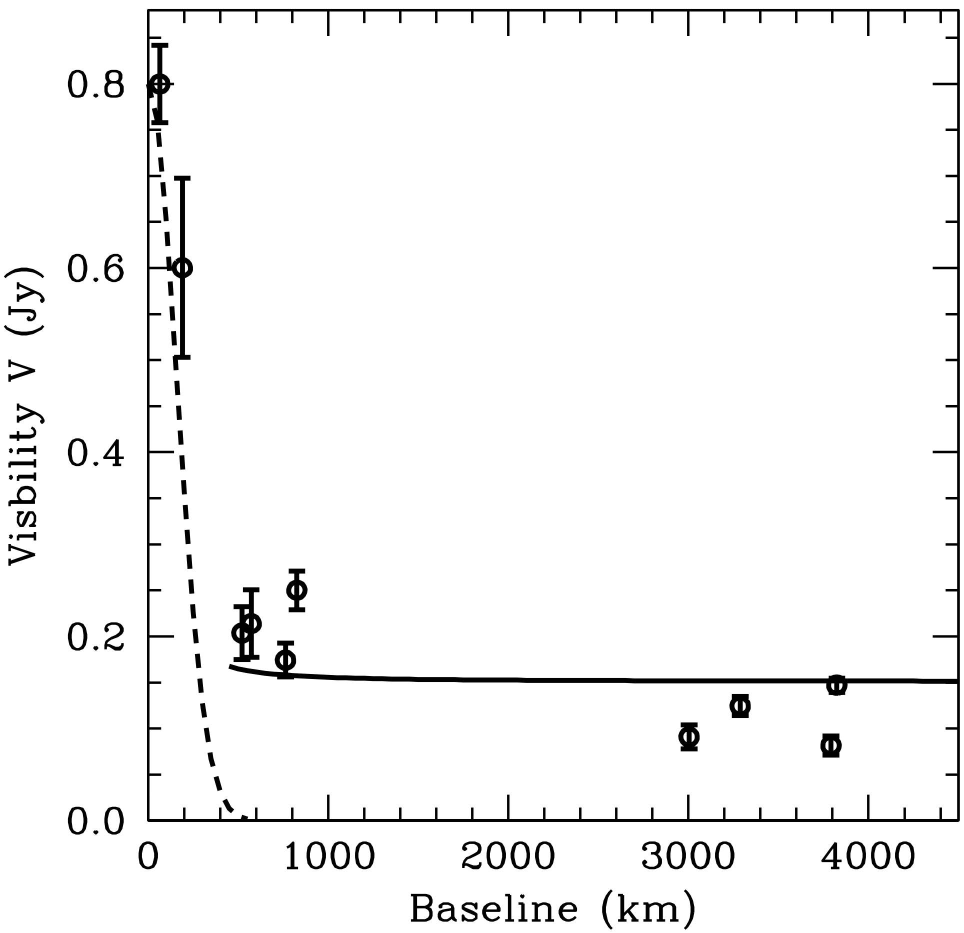
Theory by Goodman & Narayan (1989) predicts refractive contributions on such long baselines, but with different statistics.



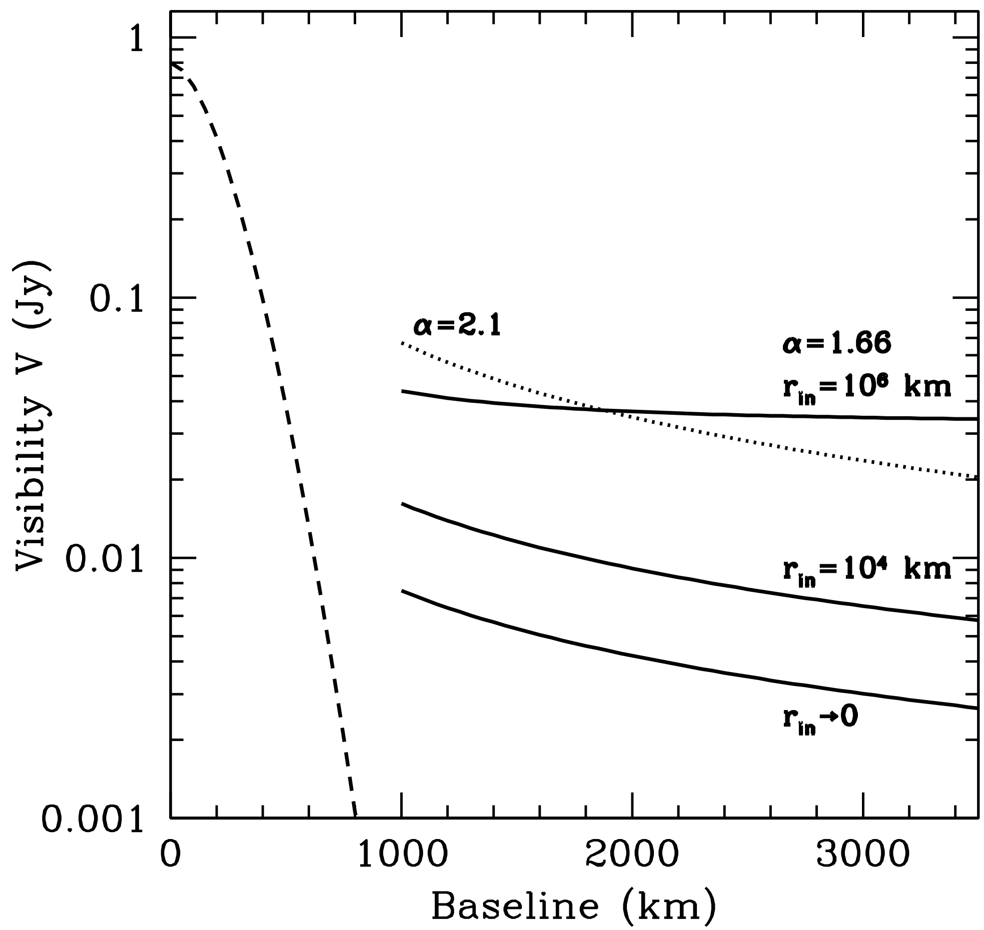
Calculations for an ideal case.
Both assume Kolmogorov spectrum.
Left: Inner scale=0.
Right: Inner scale=50×S_{ISS}

Scattering of the Galactic Center Source Sgr A* May Show Visibility on Long Baselines

Observations: Kellerman et al. 1977 observed high visibility on long baselines.



Theory: Model of Goodman & Narayan 1989 would predict much lower, but detectable, visibility.



Theory says: Source Structure Adds a Second Fourier Transform

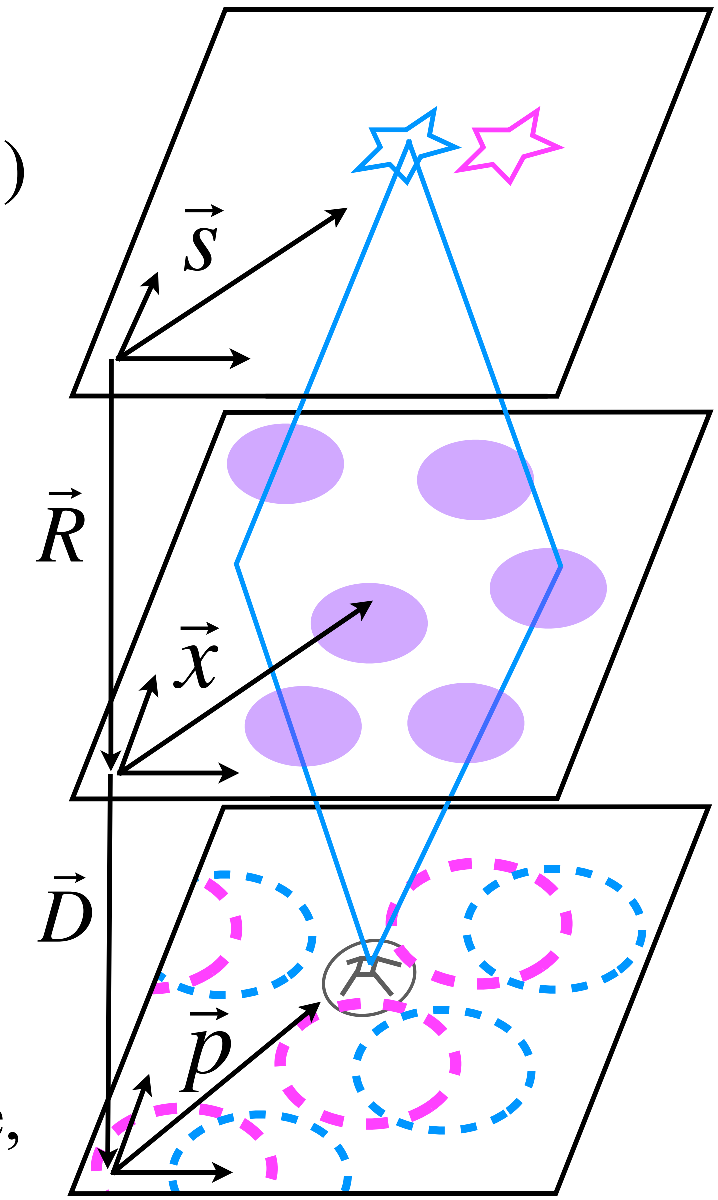
$$E(\vec{p},t) \approx \int d\vec{x}\, \frac{e^{-i\frac{k}{D}(\vec{p}\cdot\vec{x})}}{D} e^{i\Phi(\vec{x})} \int d\vec{s}\, \frac{e^{-i\frac{k}{D}(\vec{s}\cdot\vec{x})}}{D} E(\vec{s})$$

$$\Phi(\vec{x}) = \phi(\vec{x}) + k\left(\frac{1}{2D} + \frac{1}{2R}\right)x^2$$

For an incoherent source, the intensity in the observer plane is an image of the source, convolved with the response of the screen to a point source.

For a large source, and small S_{ISS}, scattering washes out the image.

But: if the scattering disk contains substructure, an image of the source might be recoverable.



Summary Questions:

- What causes the fractal structure of fringes on long baselines?
  - ✶What optical effects contribute?
  - ✶What physics in the scattering plasma produces the structures responsible?
- Do extended sources such as AGN have substructure in the scattering disk?
  - ✶Is there a relation of this substructure to effects such as intra-day variability?
  - ✶Can we learn about AGN from these structures?
- What further observations will best help to answer these questions?