Radioastron Early Science Program: Pulsars

Pulsar Working Group
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and collaborators...

Radioastron Early Science Program: Pulsars

- ✓ 24 observing sessions
  - ✳ Participating ground antennas included:

    Arecibo, Westerbork, Effelsberg, Green Bank, Effelsberg, Evpatoria, Kalyazin, Parkes, Tidbinbilla, Robledo, Hartebeesthoek, European VLBI Network, US Very-Long Baseline Array, Australia Long Baseline Array, and others..
- ✓ Fringes on baselines to 300,000 km
- ✓ Correlation:
  - ✳ single-pulse correlator
  - ✳ ASC Correlator
- ✓ Analysis: in progress
- ✓ Publications: in preparation

Outline:
Discussion of Results

Strong Scattering: Corrupt Lenses:

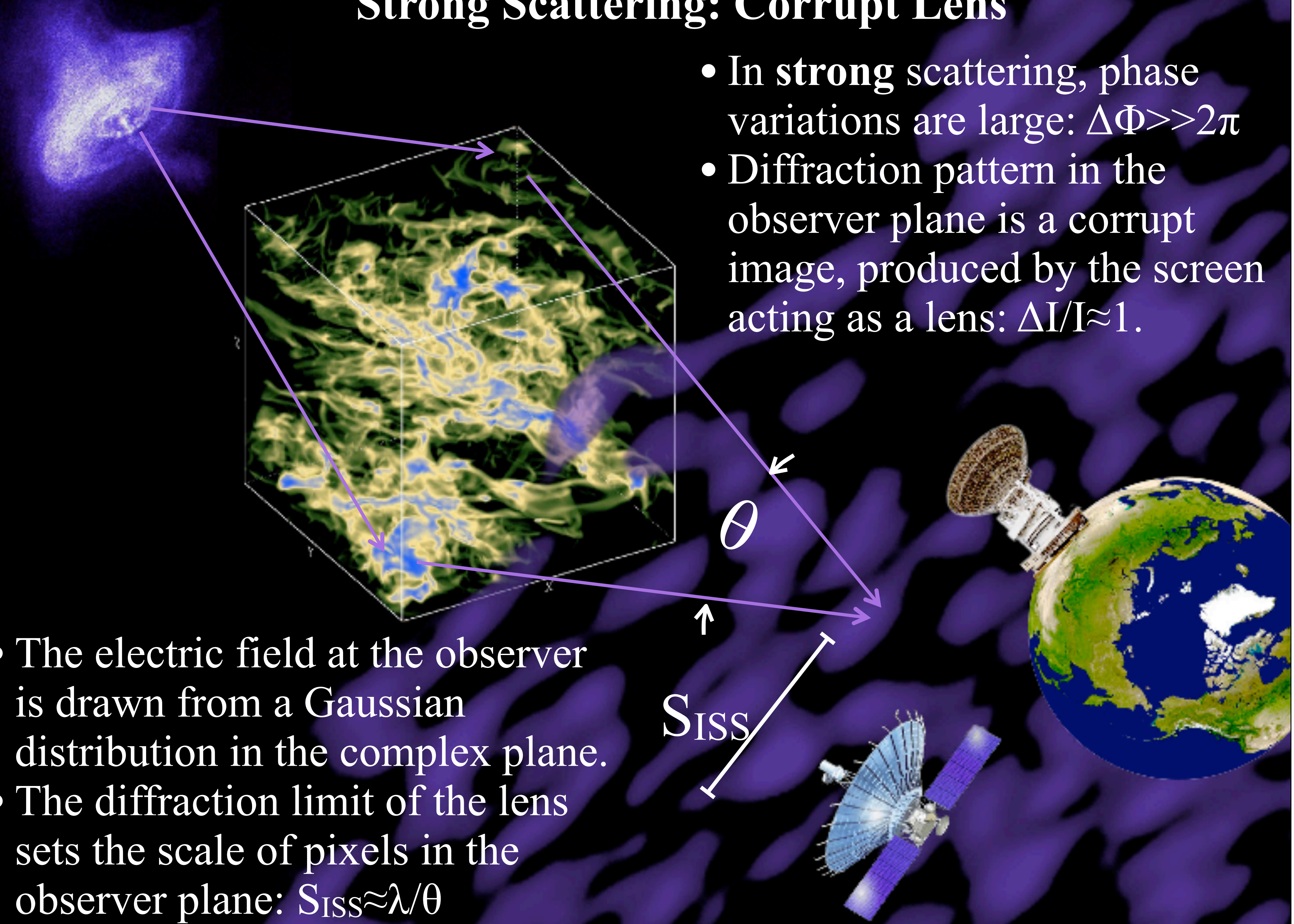
1. Vela Pulsar on Long Earth-Space Baselines
2. B0329+54: a Strong Pulsar on a Range of Baselines
3. Crab Pulsar: Giant Pulses from a Young Pulsar

Weak Scattering: Shadows:

4. B0950+08: a Nearby Weakly Scattered Pulsar

Strong Scattering: Corrupt Lens

- In **strong** scattering, phase variations are large: $\Delta\Phi >> 2\pi$
- Diffraction pattern in the observer plane is a corrupt image, produced by the screen acting as a lens: $\Delta I/I \approx 1$.

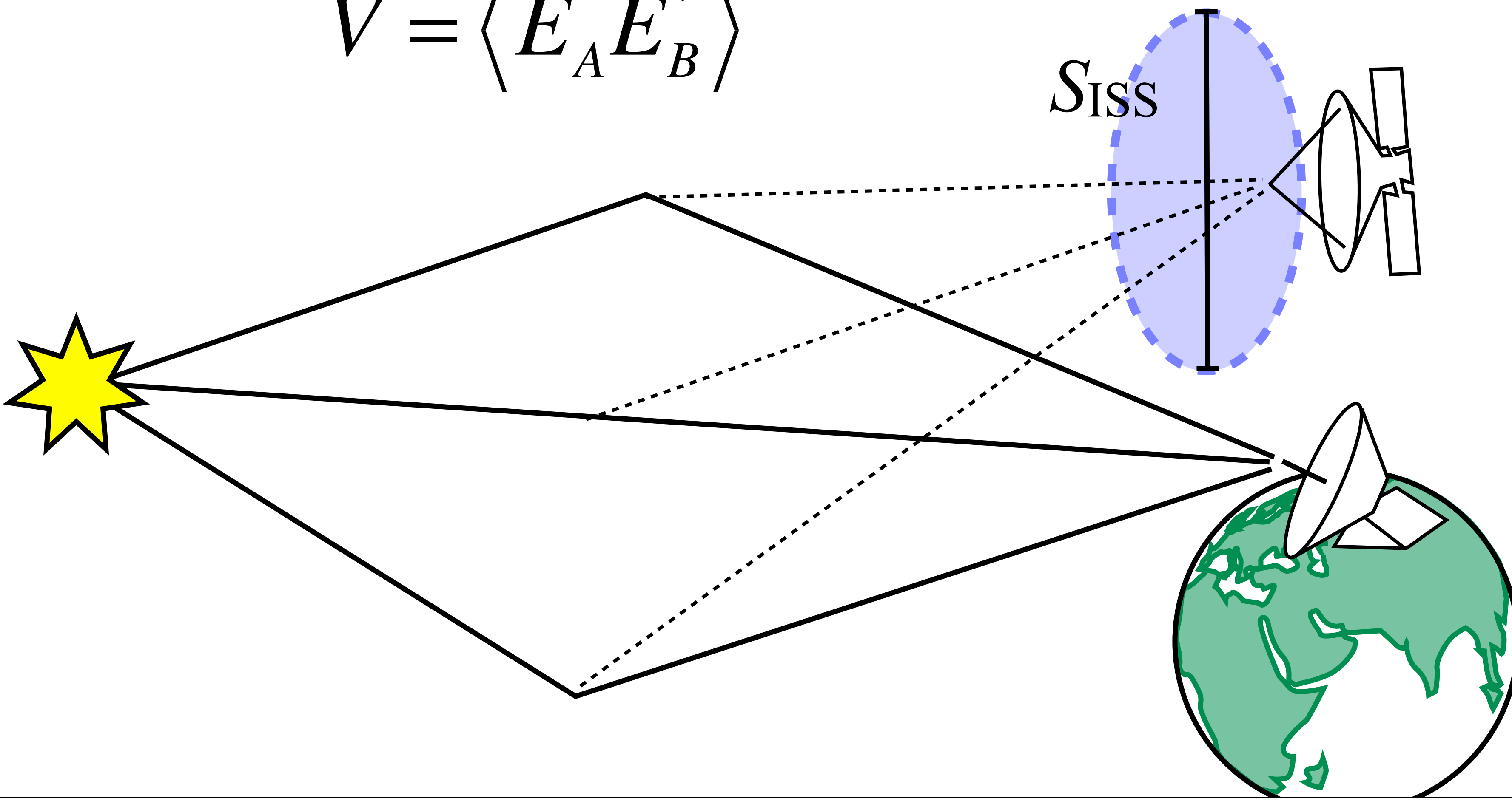


- The electric field at the observer is drawn from a Gaussian distribution in the complex plane.
- The diffraction limit of the lens sets the scale of pixels in the observer plane: $S_{ISS} \approx \lambda/\theta$

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).
- Our observable: interferometric visibility:

$$V = \left\langle E_A E_B^* \right\rangle$$



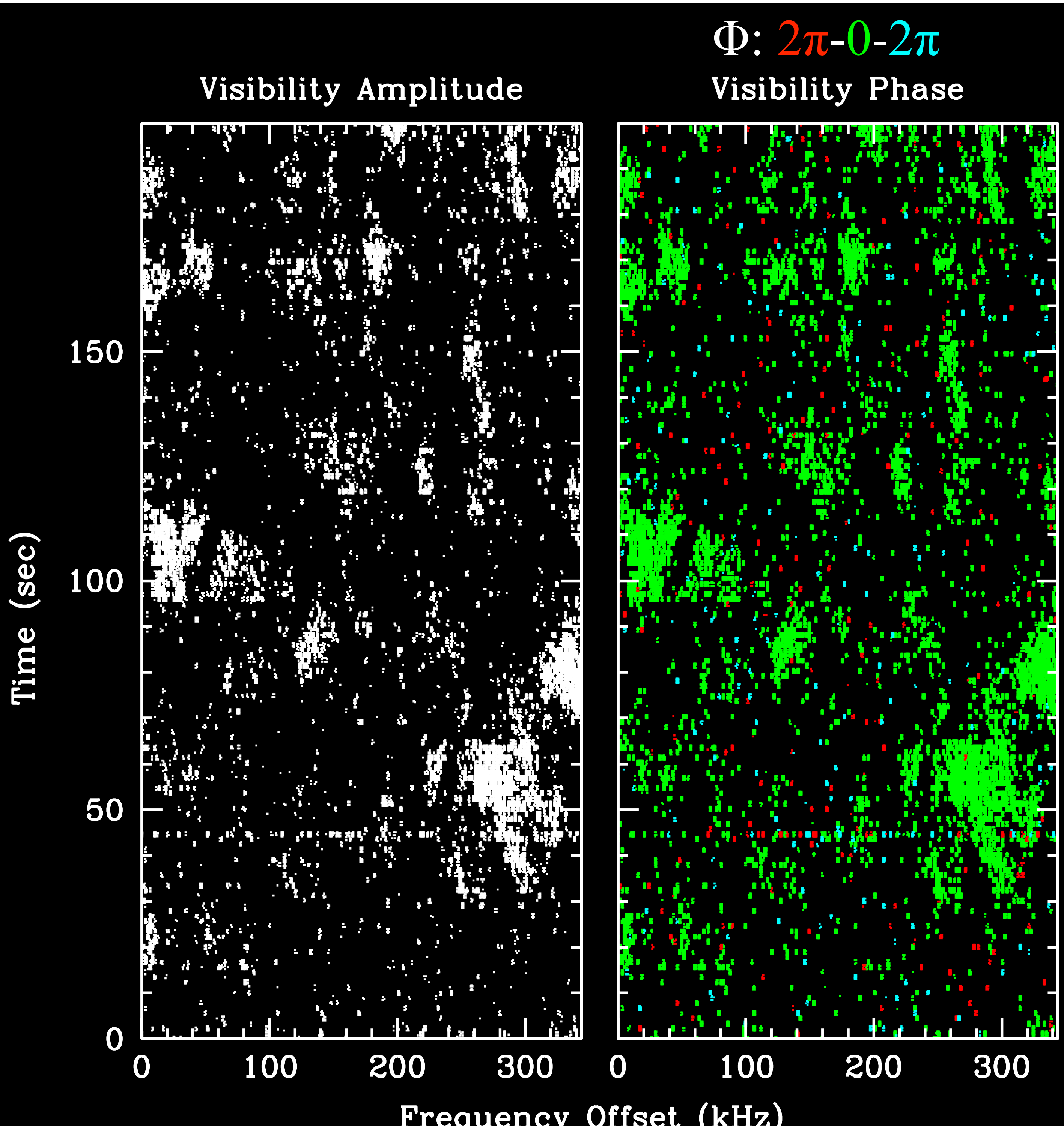
Vela Pulsar

1. Objective: Seek fringes on long baselines for this strong, heavily-scattered pulsar.

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

Vela

<u>Short baseline:</u>
Tid-Parkes.
Amplitude variations:
$\Delta V/V=100\%$
Phase variations:
$\Delta\Phi\approx0$



Vela

<u>Long baseline:</u>

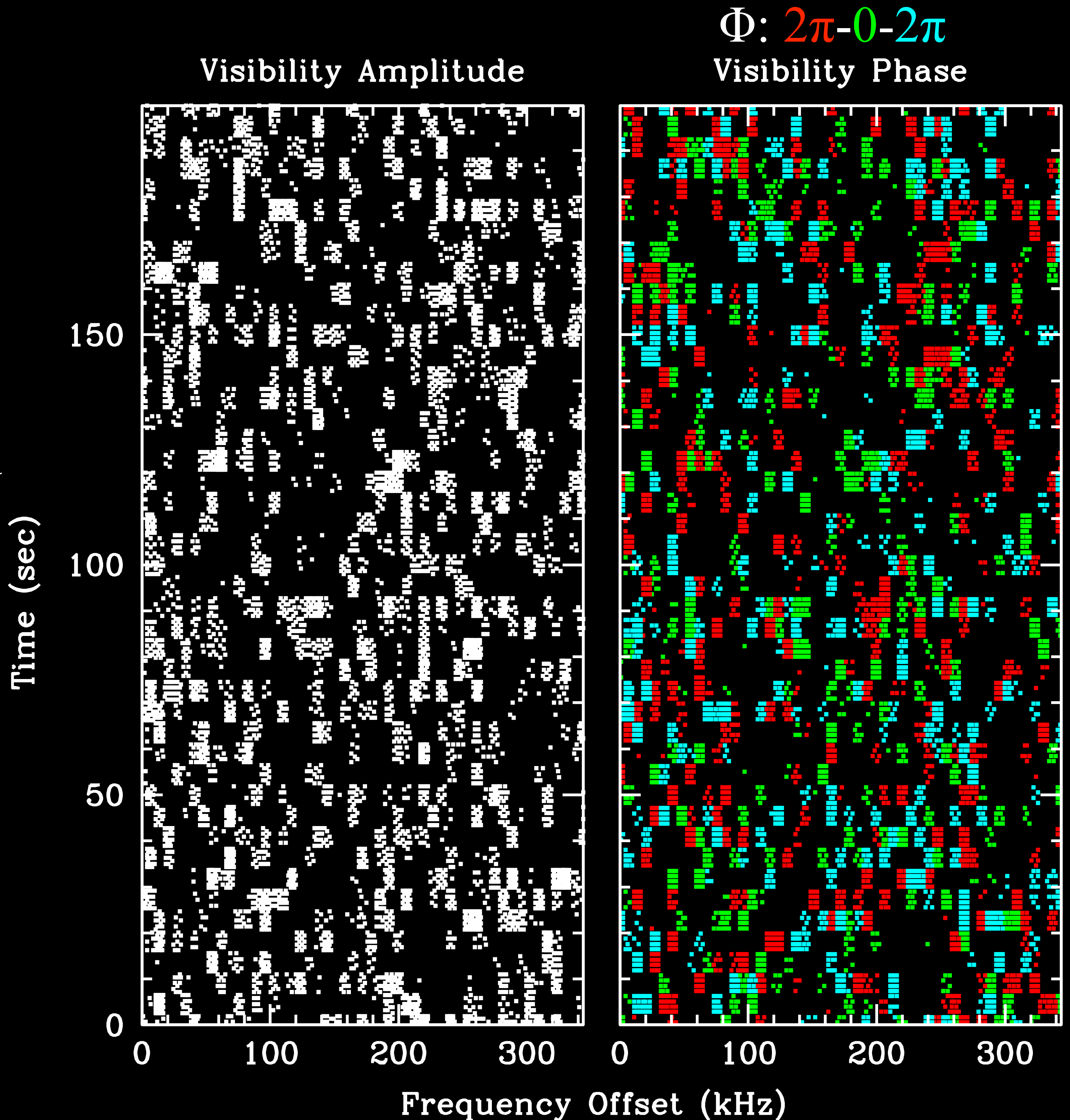
RadioAstron-Tid

Amplitude variations:

$\Delta V/V=100\%$

Phase variations:

$\Delta\Phi\approx 2\pi$



Vela

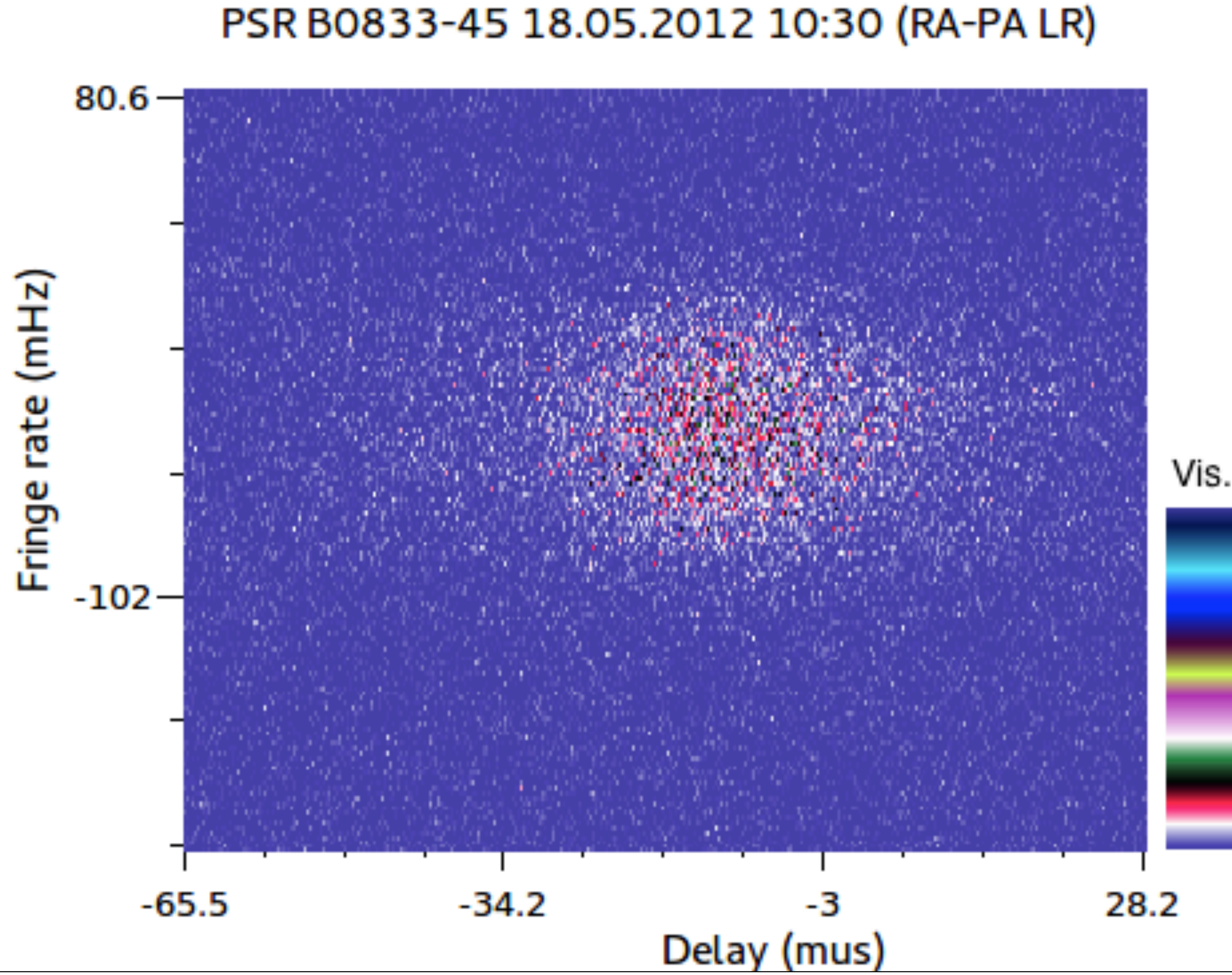
The Simplest Model for Scattering:

- 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 $\langle V \rangle = 0$ when phase variations $\rightarrow 2\pi$

Can the Simplest Model Explain All Earth-Radioastron Observations?

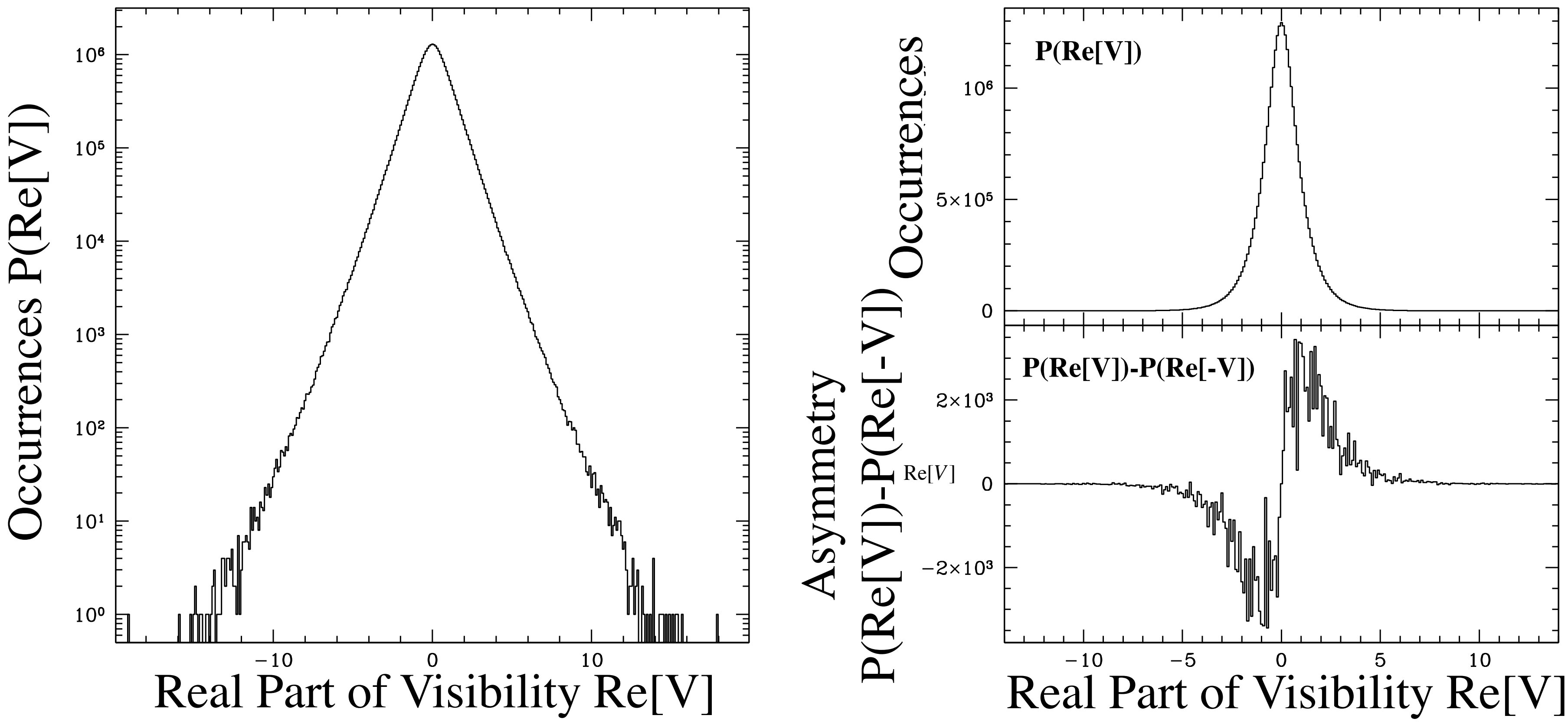
Vela

A correlation function displays complicated fringes, near a typical delay and fringe rate.



Vela Pulsar

Tidbinbilla-RadioAstron baseline shows persistent fringes



• Visibilities of individual pulses follow the expected distribution:

$$P(\mathrm{Re}[V]) = (1/2V_0)\exp\left(-\left|\mathrm{Re}[V]/V_0\right|\right)$$

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

Vela

Vela Pulsar

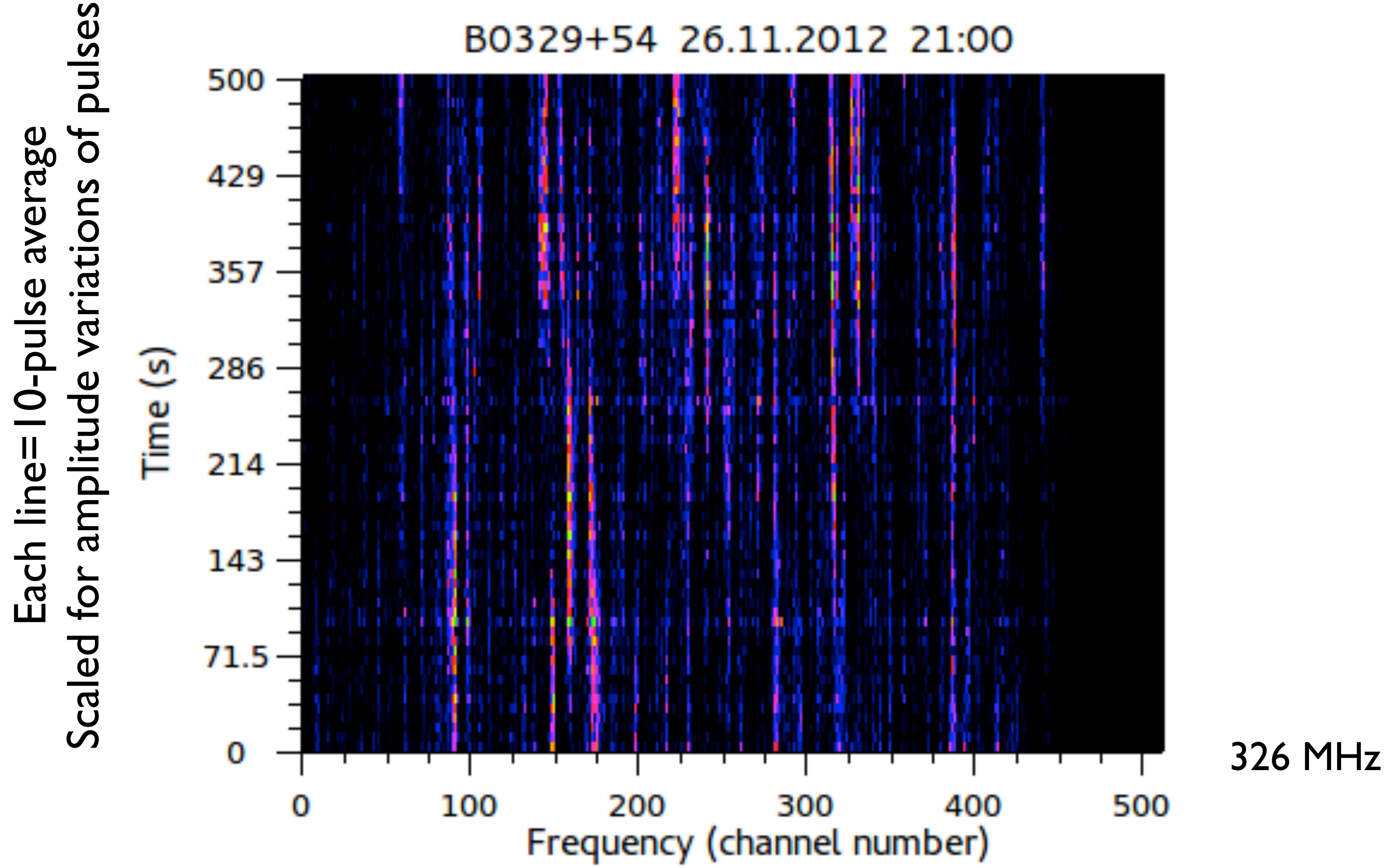
1. Objective: Seek fringes on long baselines for this strong, heavily-scattered pulsar.
2. Observations: Space-earth and Earth-earth observations at 3 epochs.
3. Results: Behavior on Earth baselines matches a simple model. On long baselines, we detect fringes in the face of large phase variations. This does not match simple models.
4. Status: Analysis in progress.

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 earth and space-earth baselines at a range of lengths.

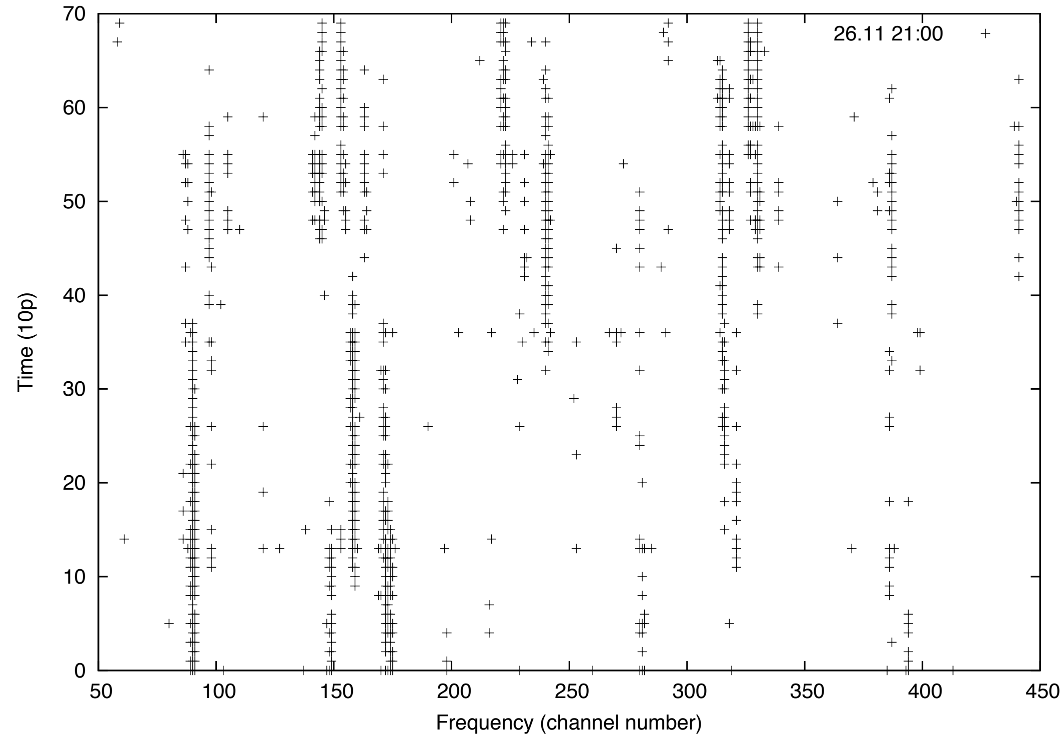
B0329+54

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

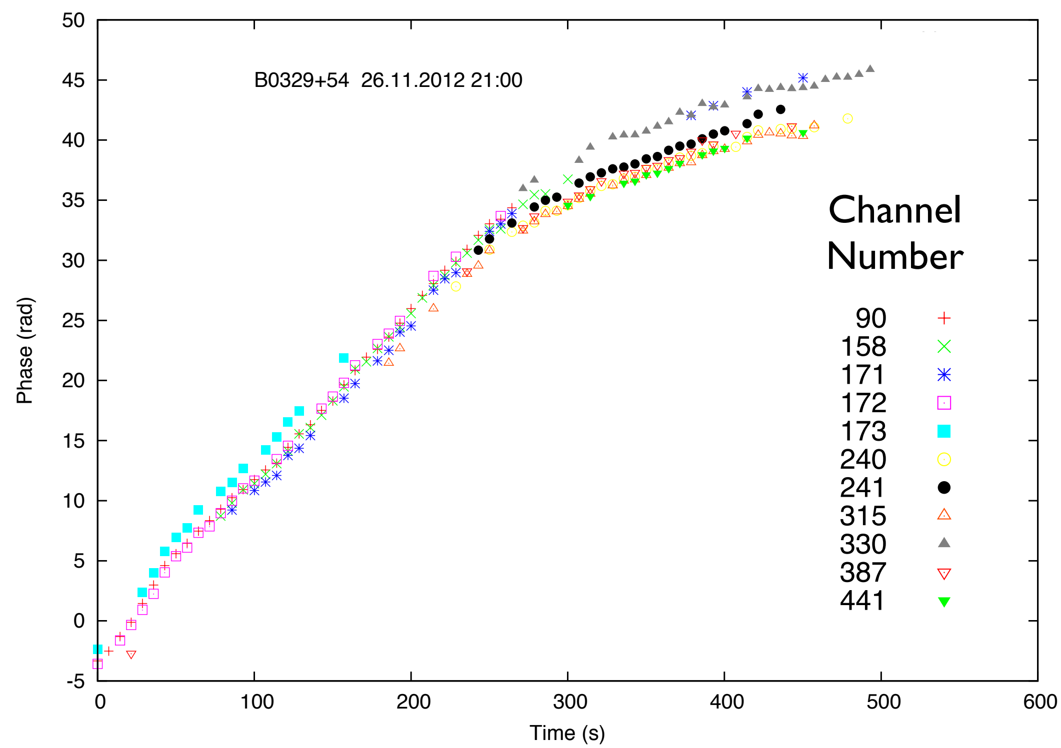


B0329+54

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

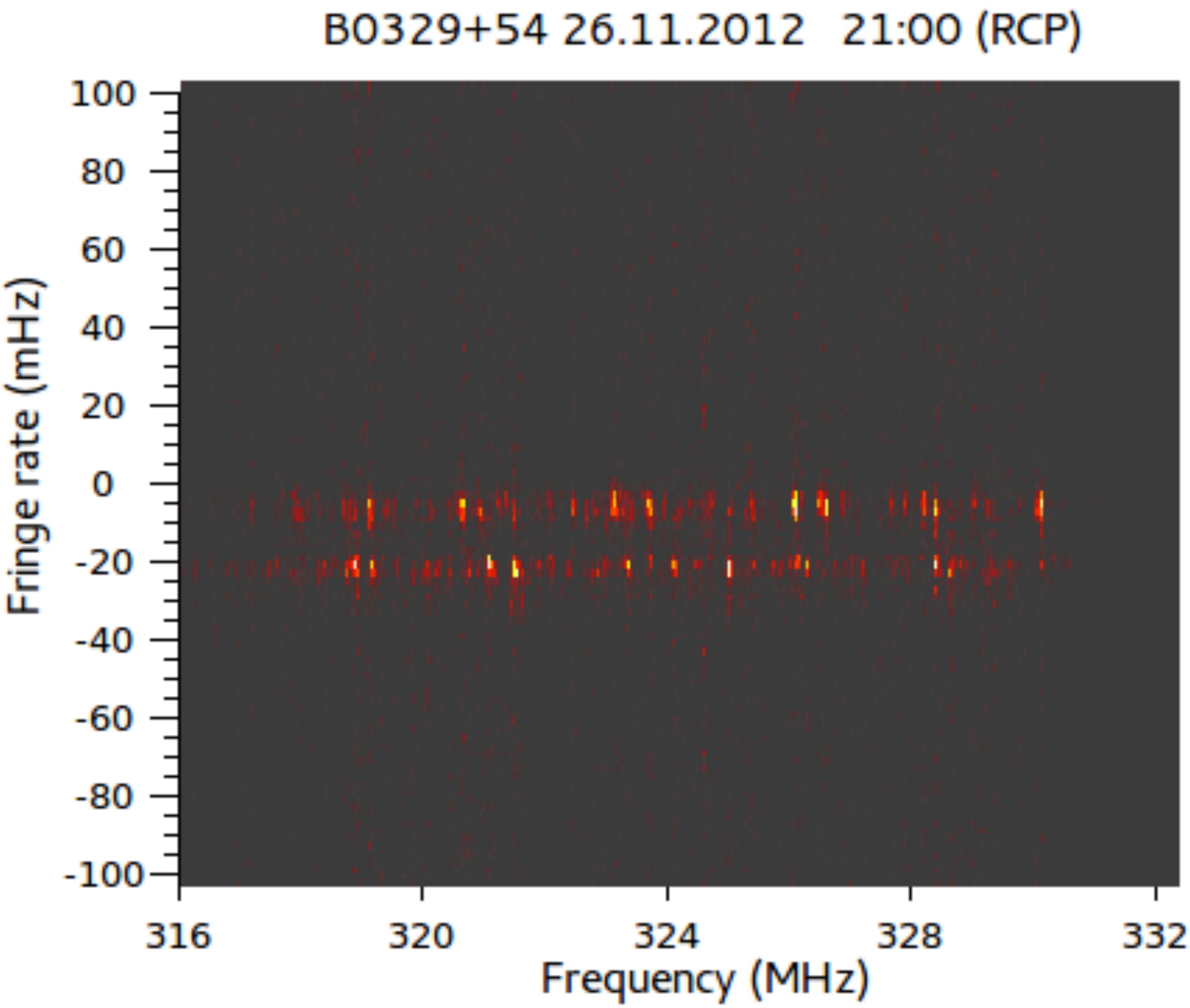


Phases vary with time, and across the spectrum. Phase variations over the source are less than 2π with frequency, for RadioAstron-GBT baseline at medium projection.



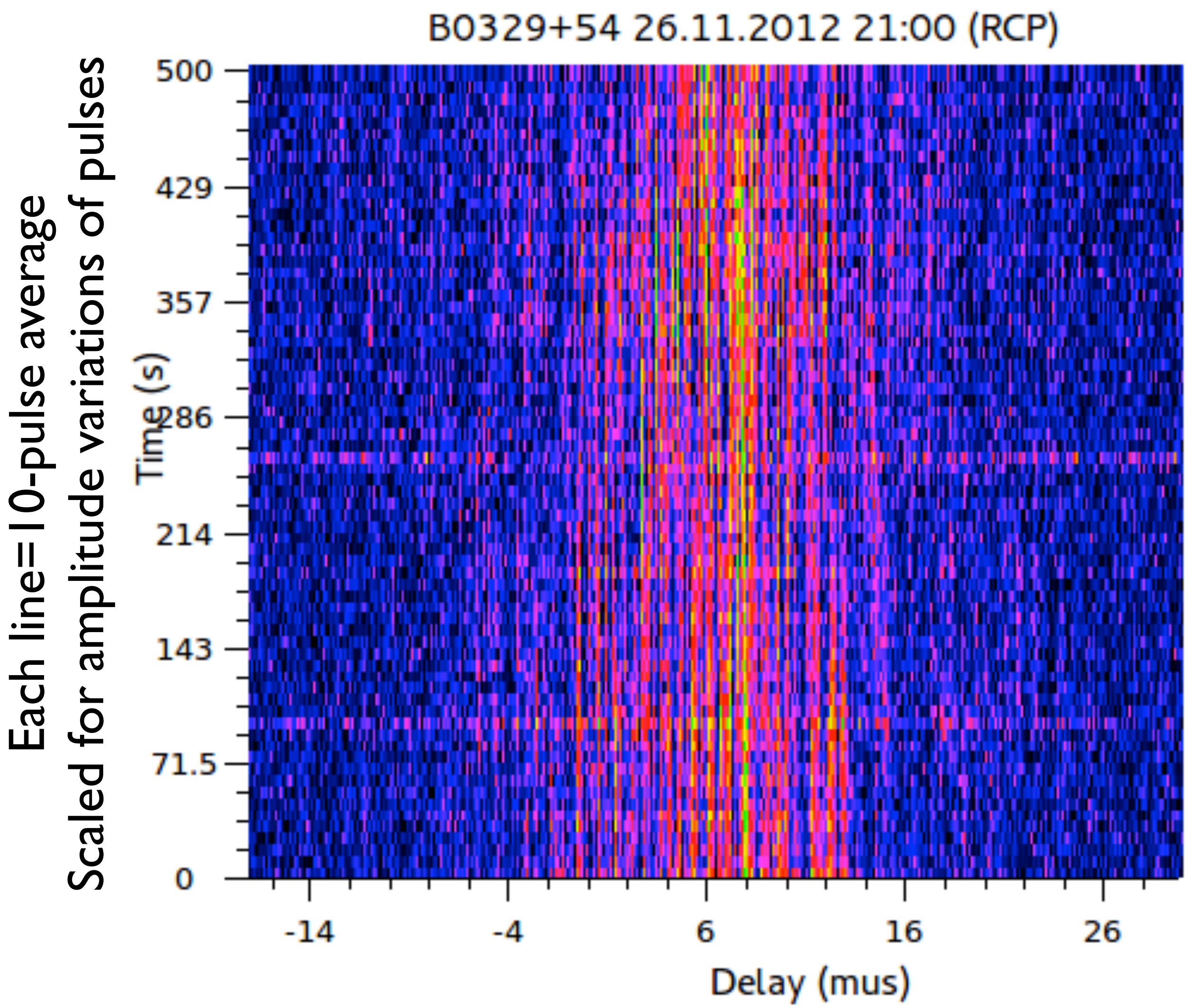
B0329+54

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



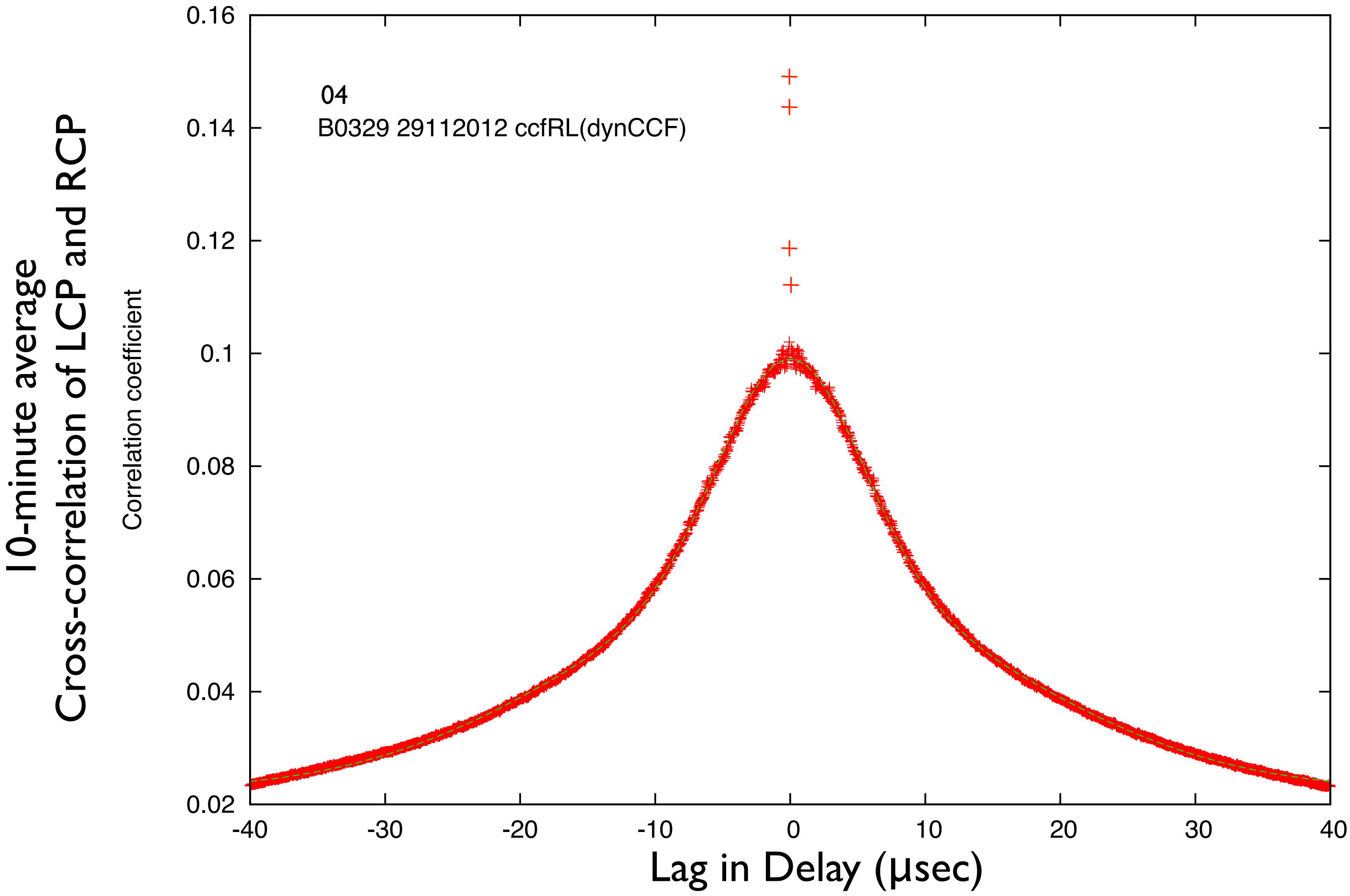
B0329+54

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



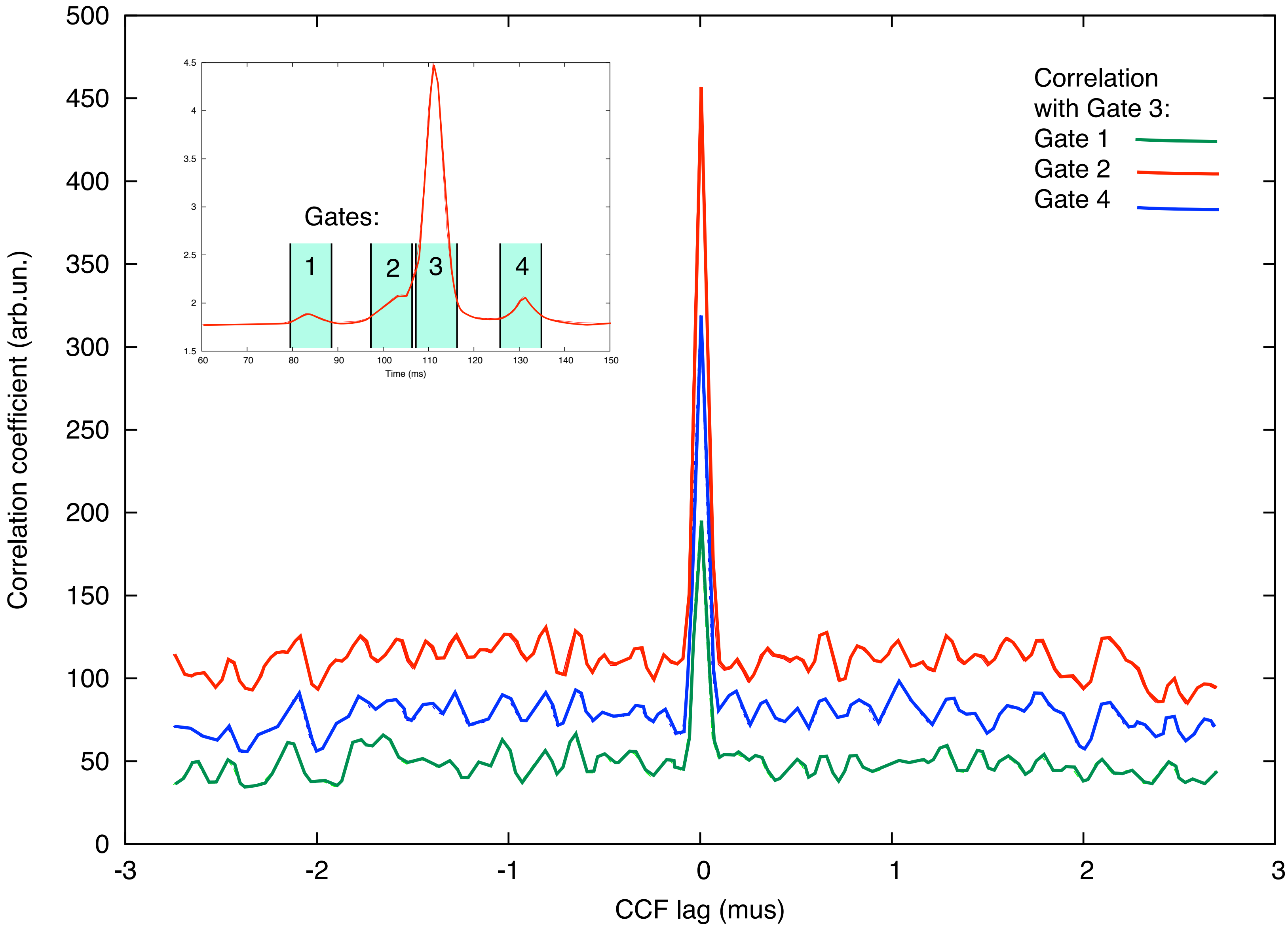
B0329+54

The correlation function in delay of RCP and LCP visibility, averaged in time, shows both large-scale and very small-scale variations.



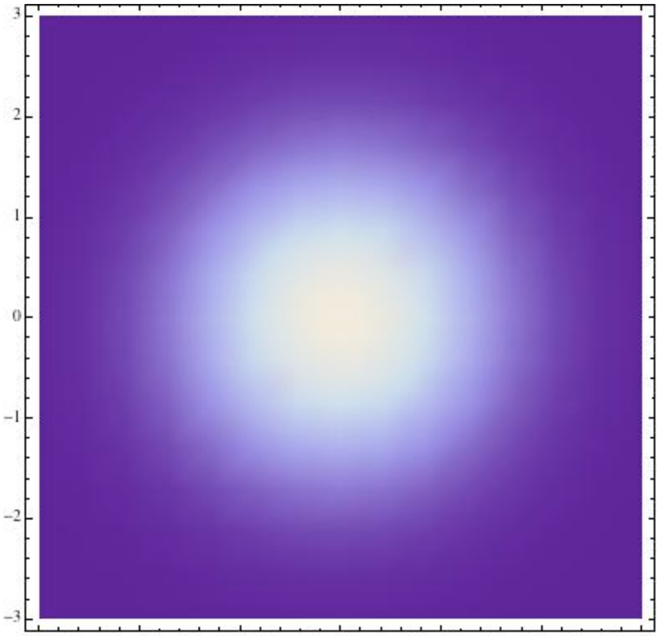
B0329+54

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



B0329+54

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



View on the Sky

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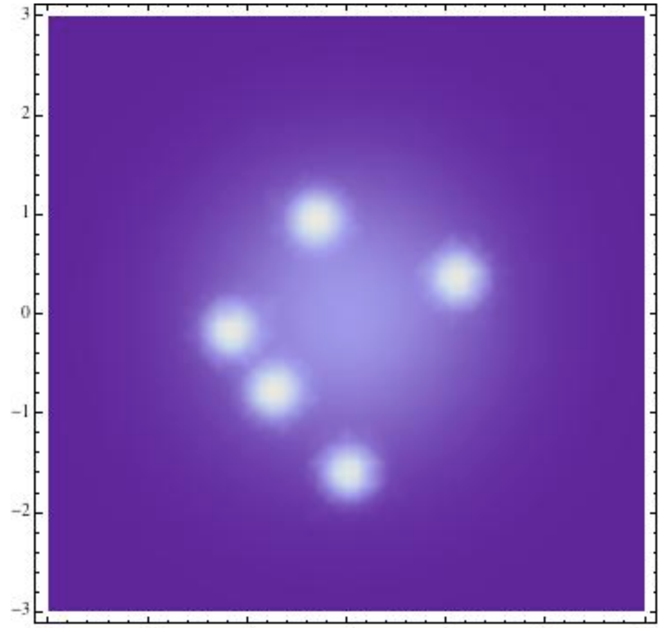
↔

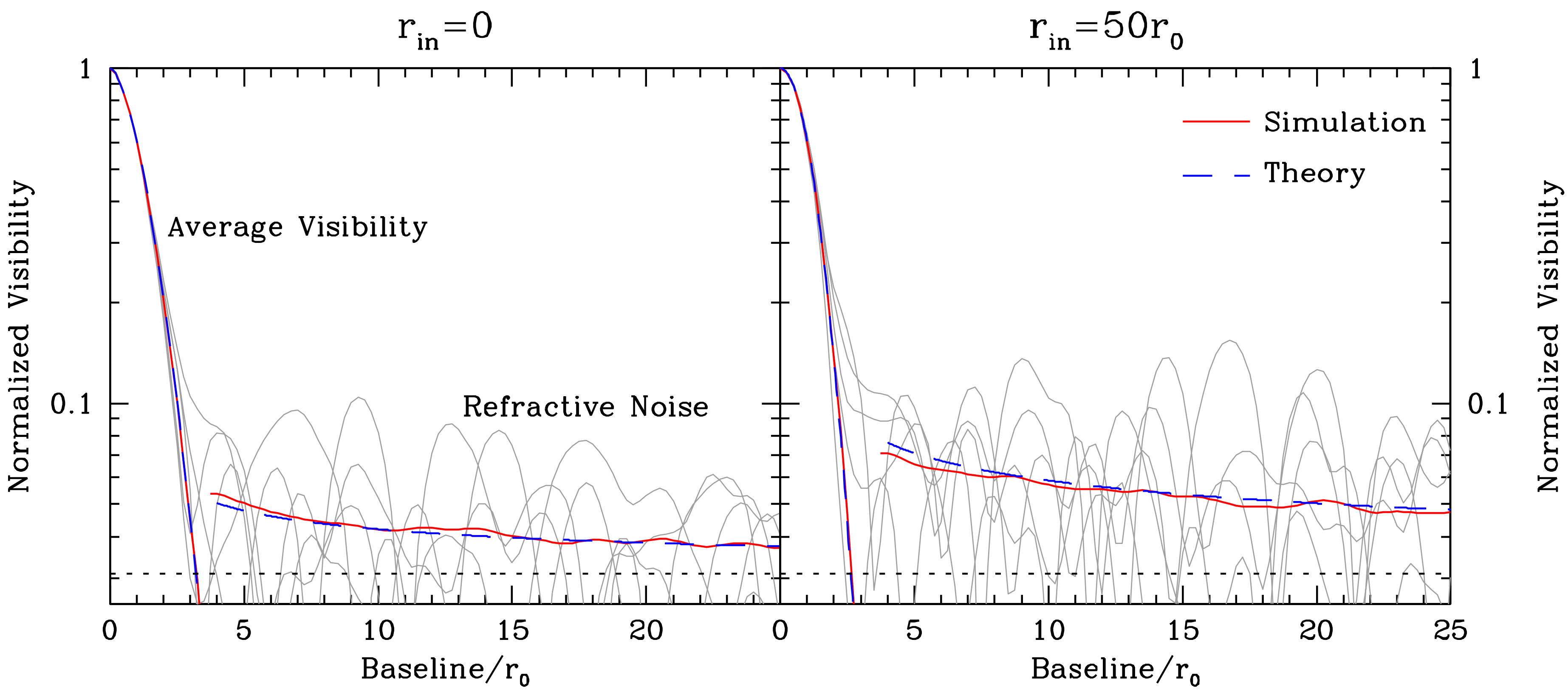


Correlation on long baselines indicate small-scale structures in the screen.

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.

B0329+54

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



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

B0329+54

Pulsar B0329+54

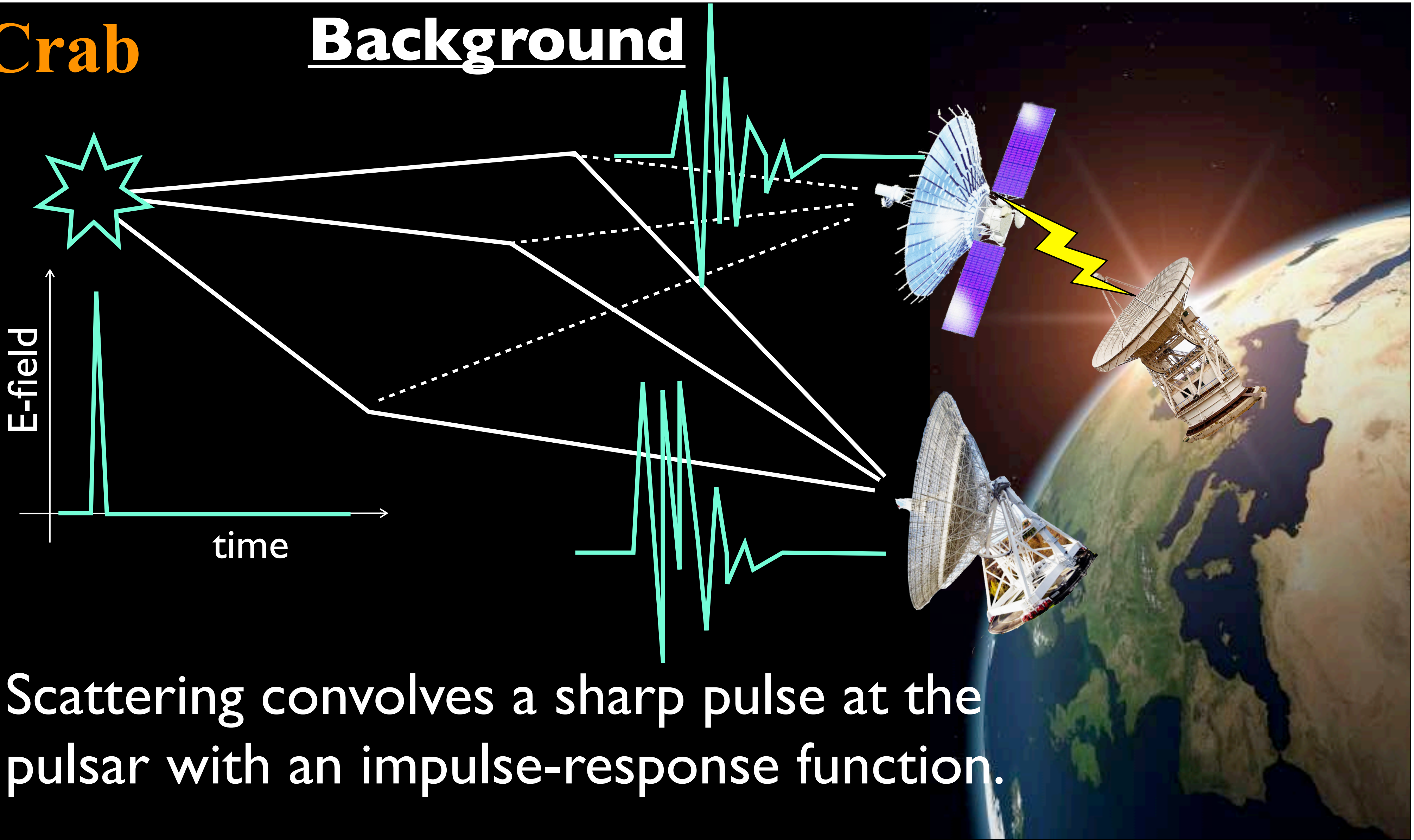
1. Objective: Understand visibility on long baselines by studying the transition from short earth-earth to long space-earth baselines.
2. Program: Study visibility on a wide range of baselines of this strong, moderately-scattered pulsar.
3. Observations: Several observations with earth and space-earth baselines at a range of lengths.
4. Results: Significant visibility on very long baselines, with rich structure. The simplest models appear to be incomplete. Evidence for substructure in scattering disk.
5. Status: Analysis in progress.

Crab Pulsar

1. Objective: Study the strong giant pulses ($\lesssim 10^5$ Jy) from this prototypical young pulsar, and perhaps use scattering in the surrounding supernova remnant as a means to study the formation of giant pulses.
2. Observations: Space-earth observations at 4 epochs.

Crab

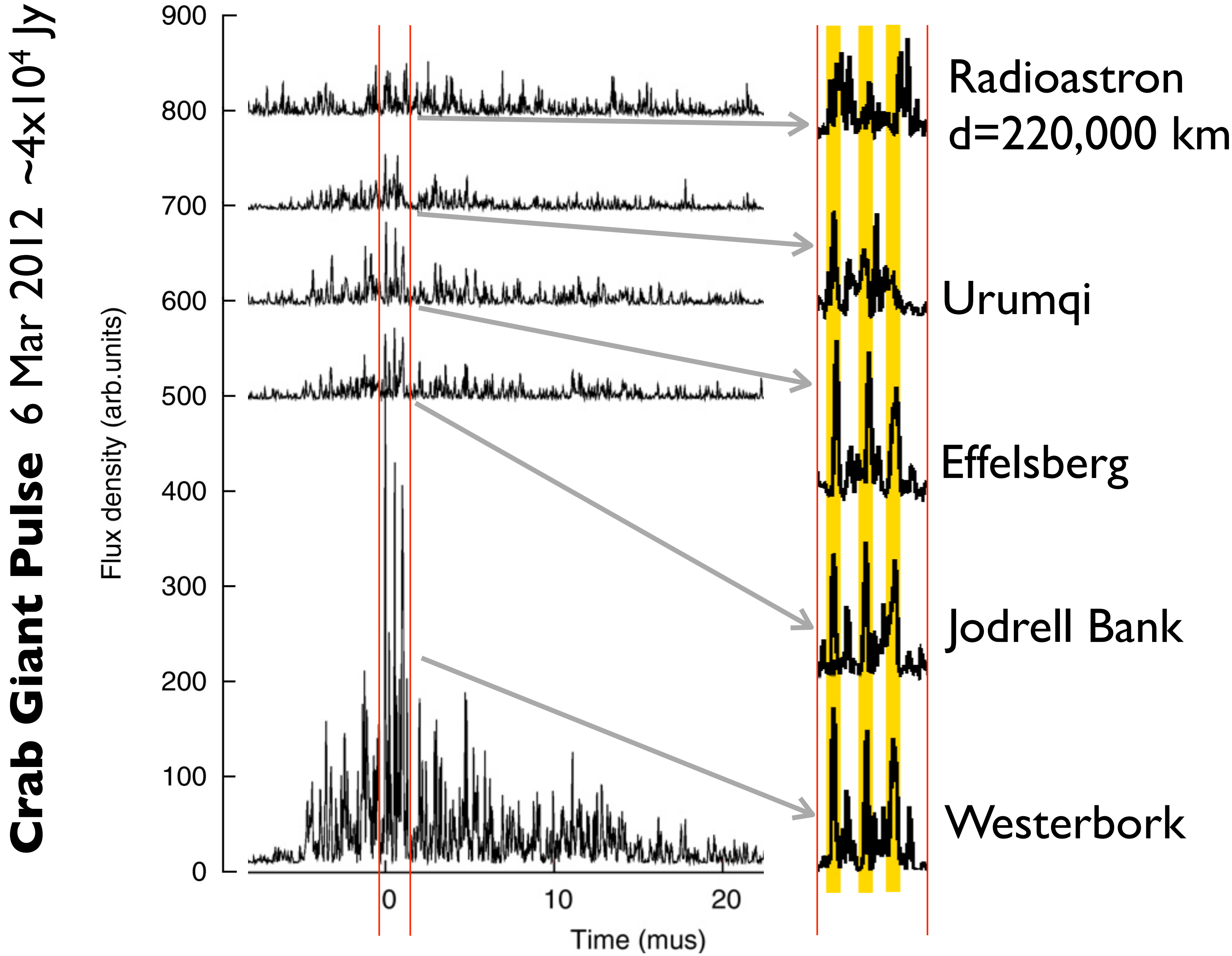
Background



Scattering convolves a sharp pulse at the pulsar with an impulse-response function.

This impulse-response function reflects reinforcement or cancellation of radiation from along different paths. Relative path lengths change with observer position.

Crab Popov et al: Study of Crab Giant Pulses



Giant pulse observed with RadioAstron and EVN, March 06 2012

Crab Pulsar

1. Objective: Study the strong giant pulses ($\lesssim 10^5$ average flux) from this prototypical young pulsar, and perhaps use scattering in the surrounding supernova remnant as a means to study the formation of giant pulses.
2. Observations: Space-earth observations at many epochs.
3. Results: Giant pulses detected, several in single-dish mode at Radioastron and Earth antennas. Some show fringes, some do not.
4. Status: Gathering more giant pulses. Seeking better understanding of long-baseline behavior and time variability.

B0950+08

Pulsar B0950+08

1. Objective: Understand scattering of this weakly-scattered pulsar. Previous work suggested that this pulsar is scattered by very nearby material.
2. Observations: RadioAstron-Arecibo baselines to 220,000 km.

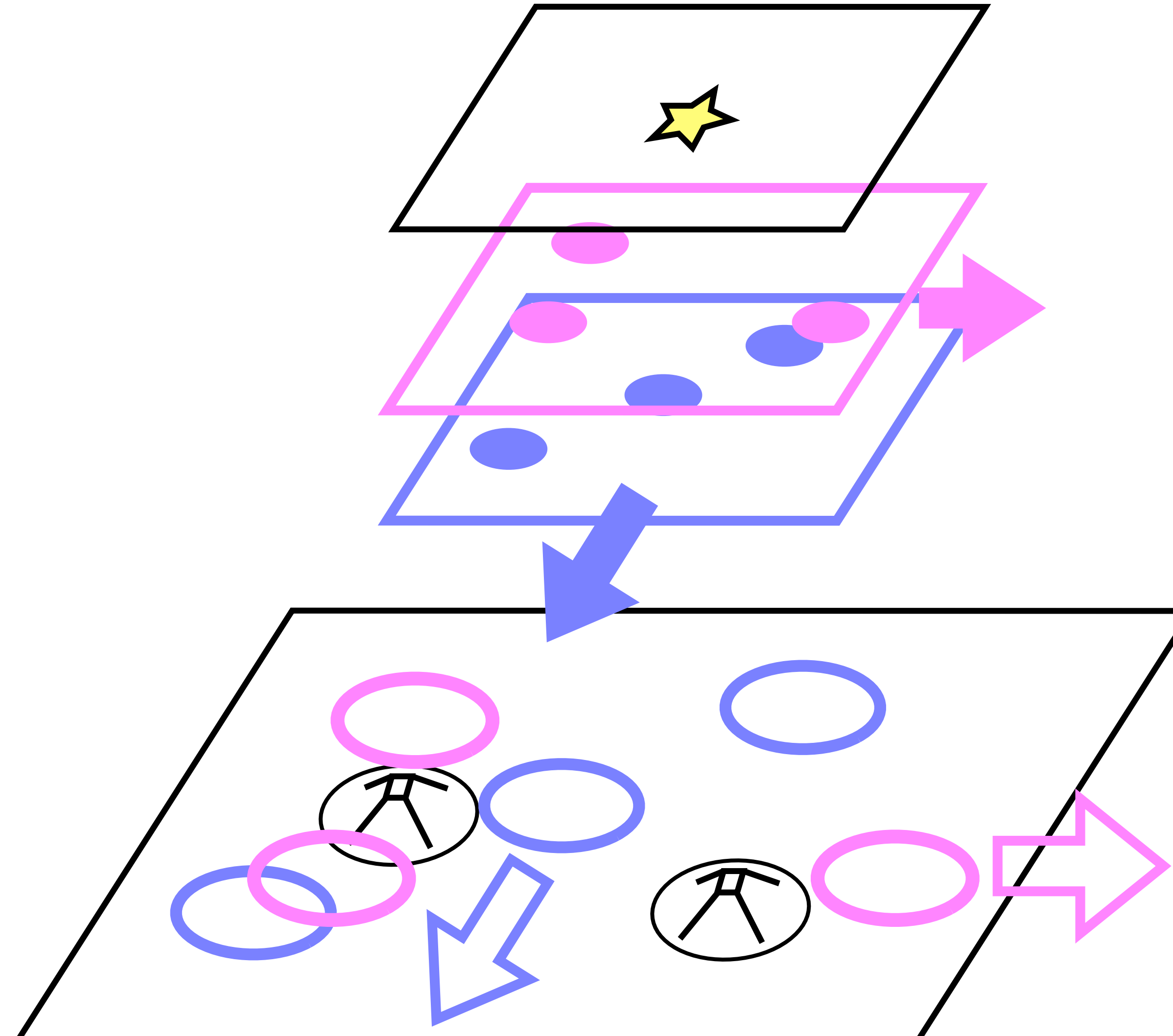
B0950+08

Weak Scattering: Shadow Graph

In **weak** scattering, phase variations are small: $\Delta\Phi << 2\pi$

Pattern in the observer plane is a projection of the screen: $\Delta I/I << 1$.

Different screens can be distinguished by their speeds.



B0950+08

Weak Scattering: Shadow Graph

In **weak** scattering, phase variations are small: $\Delta\Phi << 2\pi$

Pattern in the observer plane is a projection of the screen: $\Delta I/I << 1$.

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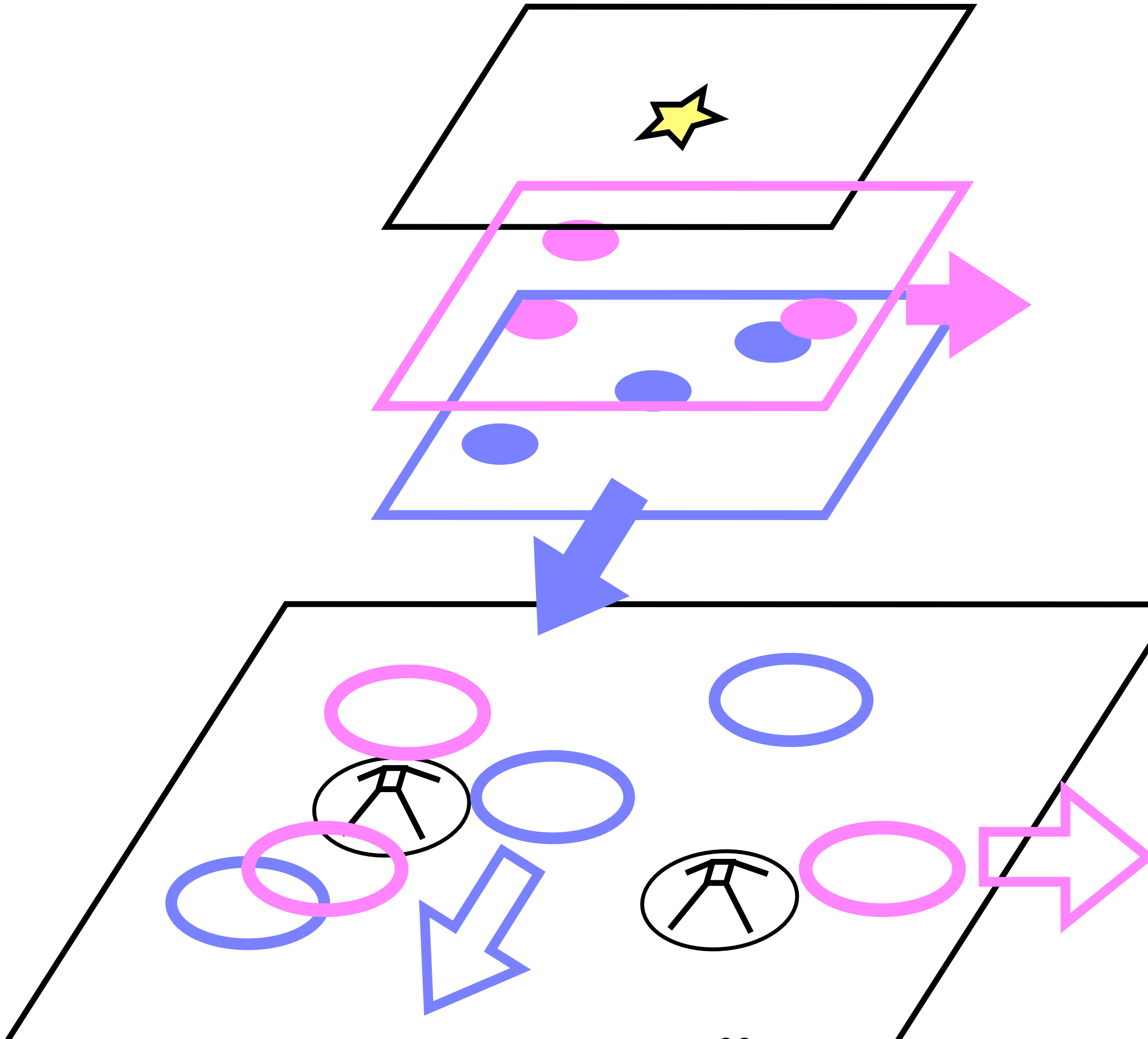
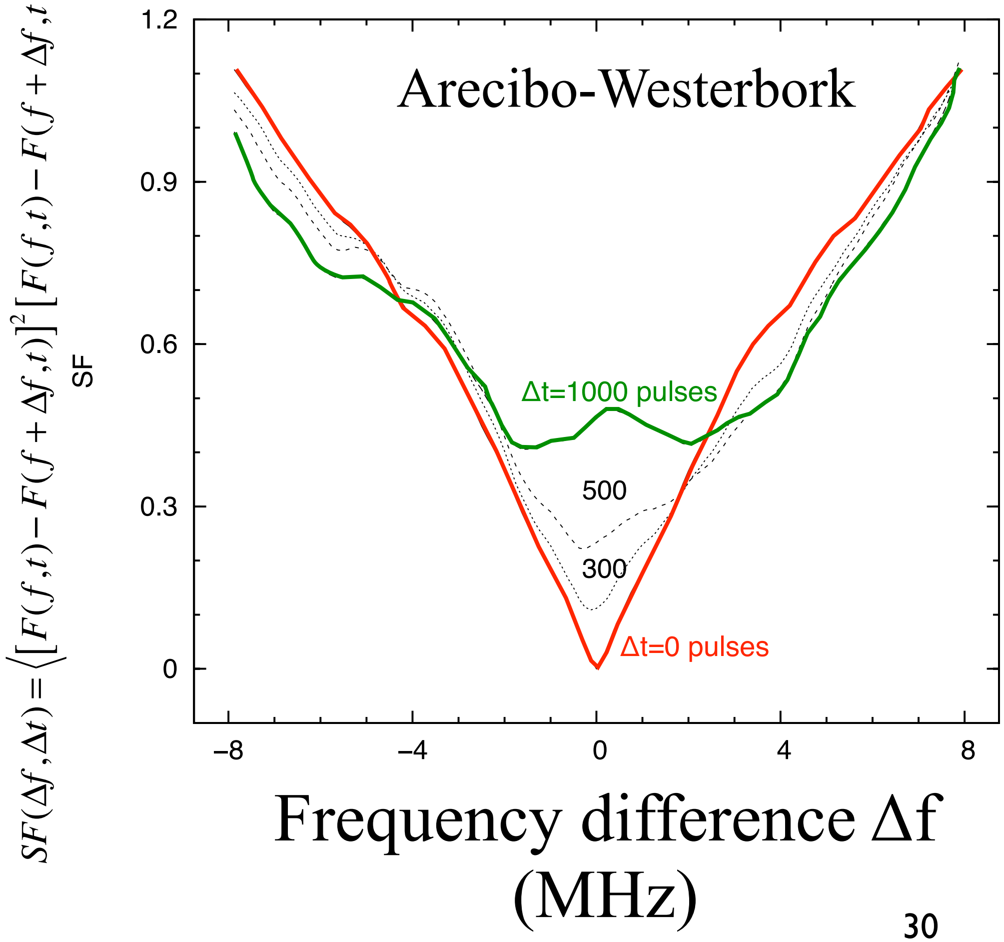
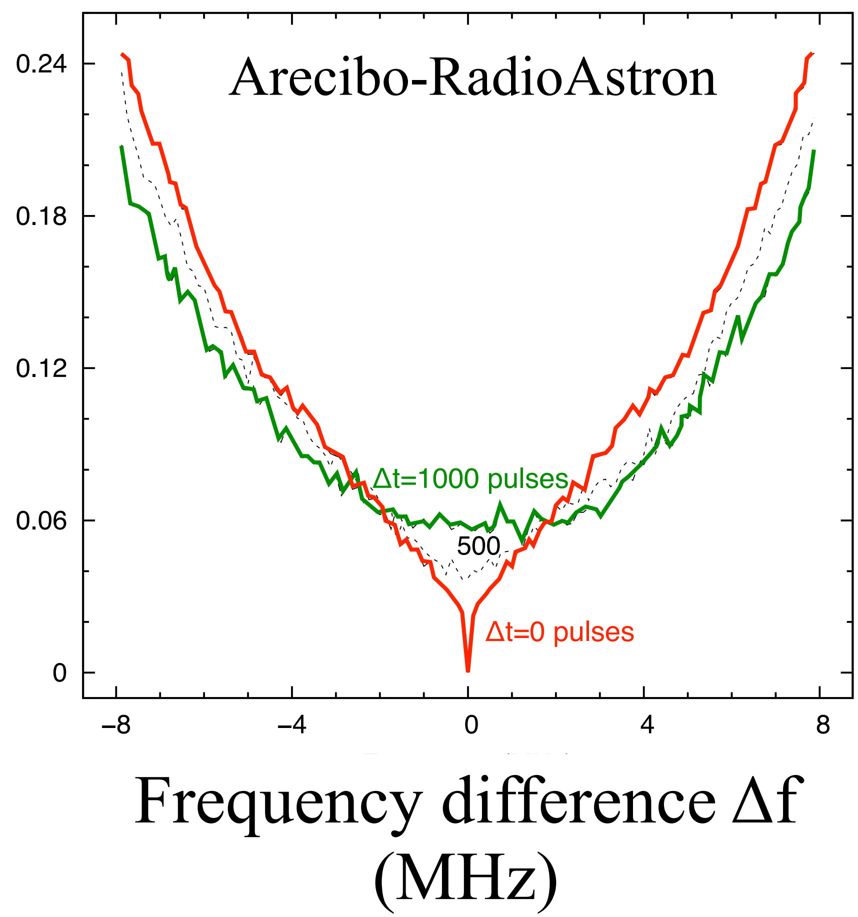


B0950+08

Smirnova et al: Study of pulsar B0950+08

- Structure Function shows 2 scales with different width in Δf for Arecibo-Westerbork baseline
- One vanishes at large Δt, and does not appear on RadioAstron-Arecibo baseline -- Indicates 2 screens of different velocities
- Models yield inferred distances: 10 and 100 pc

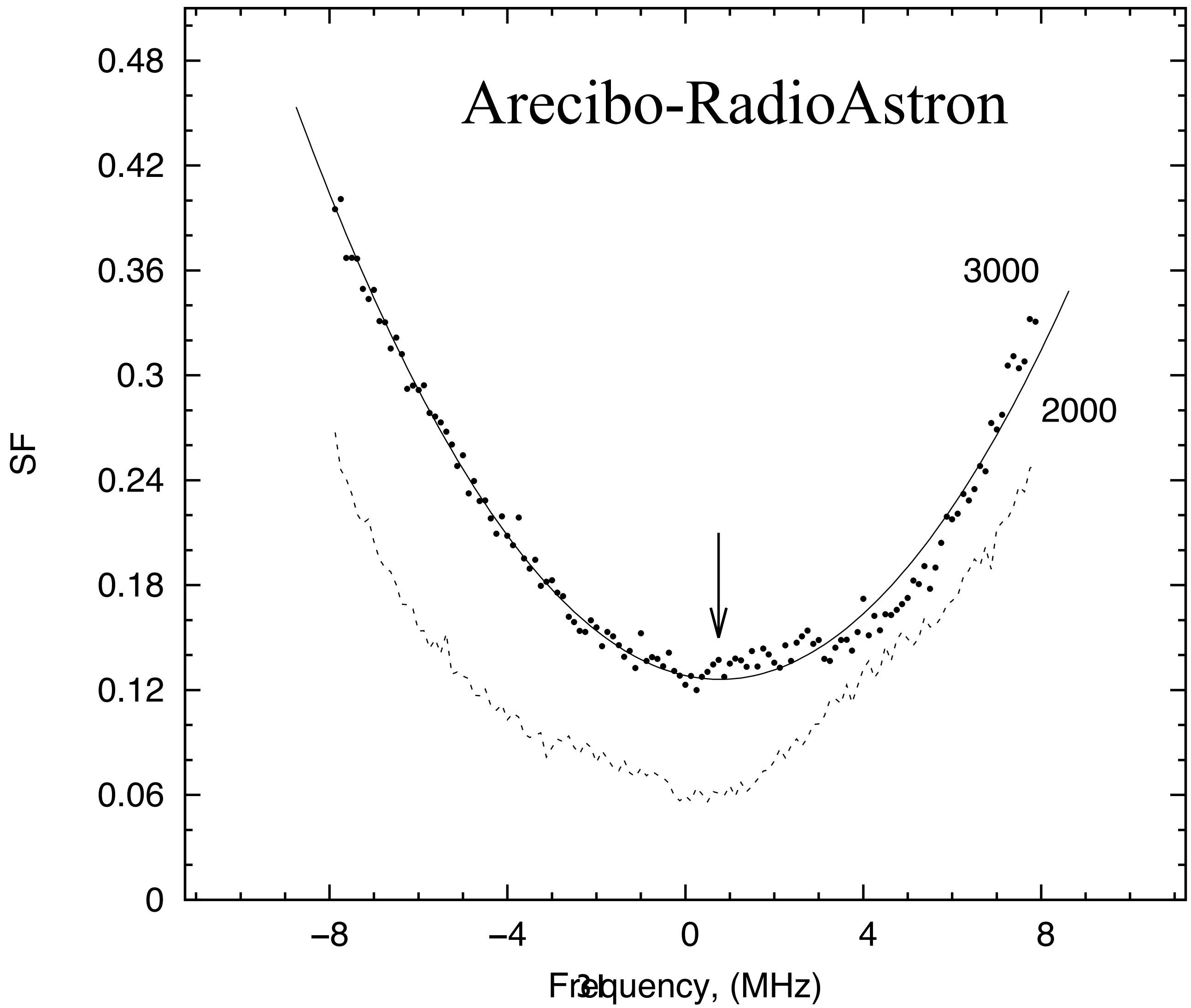




B0950+08

Mininimum in Δf of Structure Function shifts with lag in Δt --Indicates presence of refracting wedge

$$SF(\Delta f,\Delta t)=\left\langle \left[F^2(f,t)-F^2(f+\Delta f,t)\right]\left[F^2(f,t)-F^2(f+\Delta f,t+\Delta t)\right]\right\rangle$$



B0950+08

Pulsar B0950+08

1. Objective: Understand scattering of this weakly-scattered pulsar. Previous work suggested that this pulsar is scattered by very nearby material.
2. Observations: RadioAstron-Arecibo baselines to 220,000 km.
3. Results: Scattering is weak. Two screens are apparent at ≈10 pc and ≈100 pc. Strong refraction in the form of a wedge is present.
4. Status: Paper in preparation.

Radioastron Early Science Program: Pulsars

Strong Scattering: Corrupt Lenses:

1. Vela Pulsar on Long Earth-Space Baselines
2. B0329+54: a Strong Pulsar on a Range of Baselines
3. Crab Pulsar: Giant Pulses from a Young Pulsar

Weak Scattering: Shadows:

4. B0950+08: a Nearby Weakly Scattered Pulsar

Summary Questions:

- What causes the fringes of heavily-scattered pulsars on long baselines?
- Why do fringe rates change discontinuously for pulsar B0329+54?
- How does scattering affect the giant pulses of the Crab pulsar?
- What nearby plasma screen is responsible for scattering of pulsar B0950+08?
    - ✴Are other nearby pulsars scattered by this material?
    - ✴Are some Active Galactic Nuclei scattered by it?