Scintillating Pulsars

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Why Observe Pulsars with VLBI?

- Astrometry
- Scattering
  - Scattering disks
    - Dist of scattering material
      - Nearby pulsars for radioastron!
    - Shape of Scattering Disk
      - Cusps or Parabolic Arcs?
  - Structure of pulsar emission regions
- Technical Notes on Pulsar VLBI

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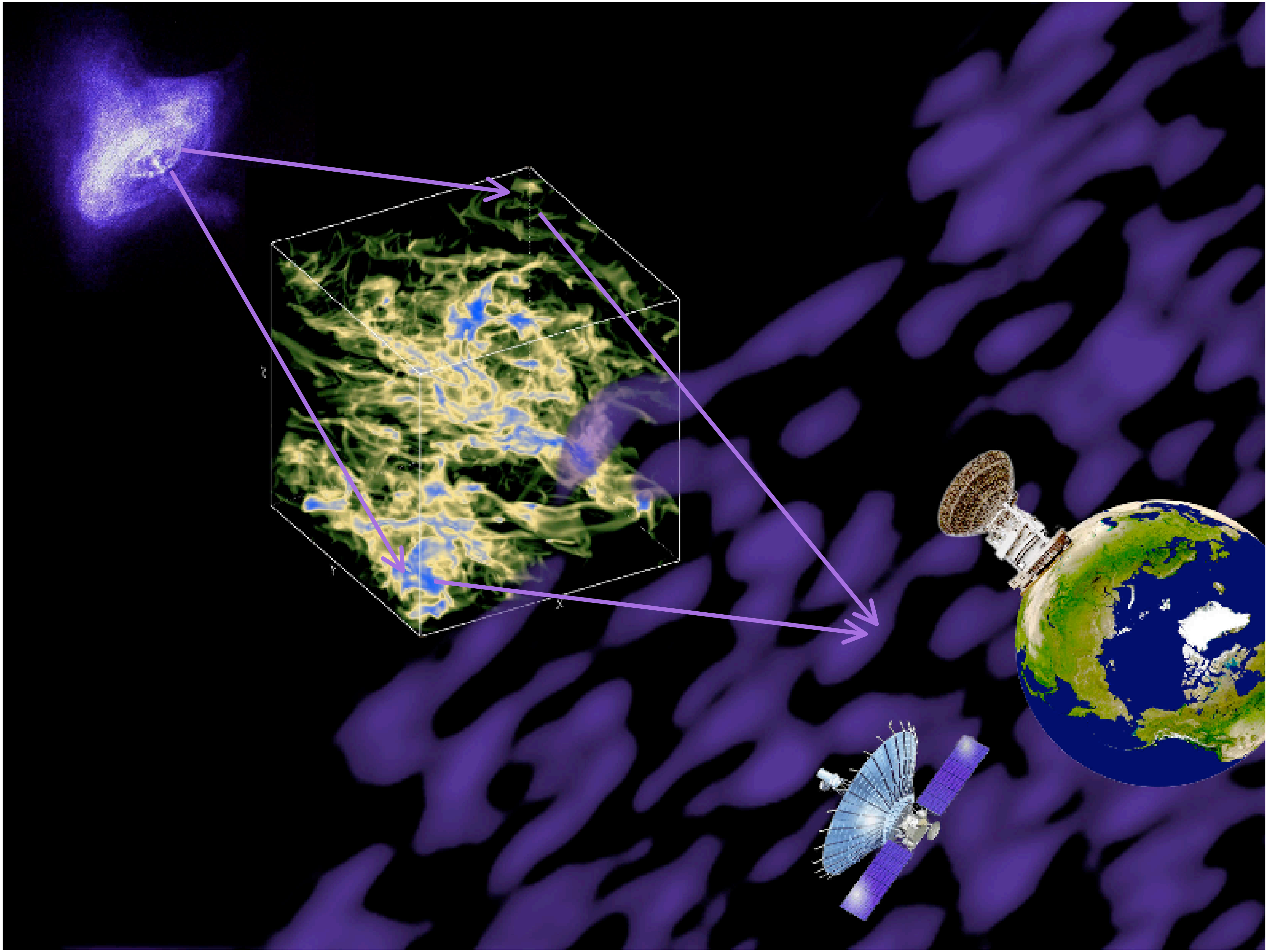
Introduction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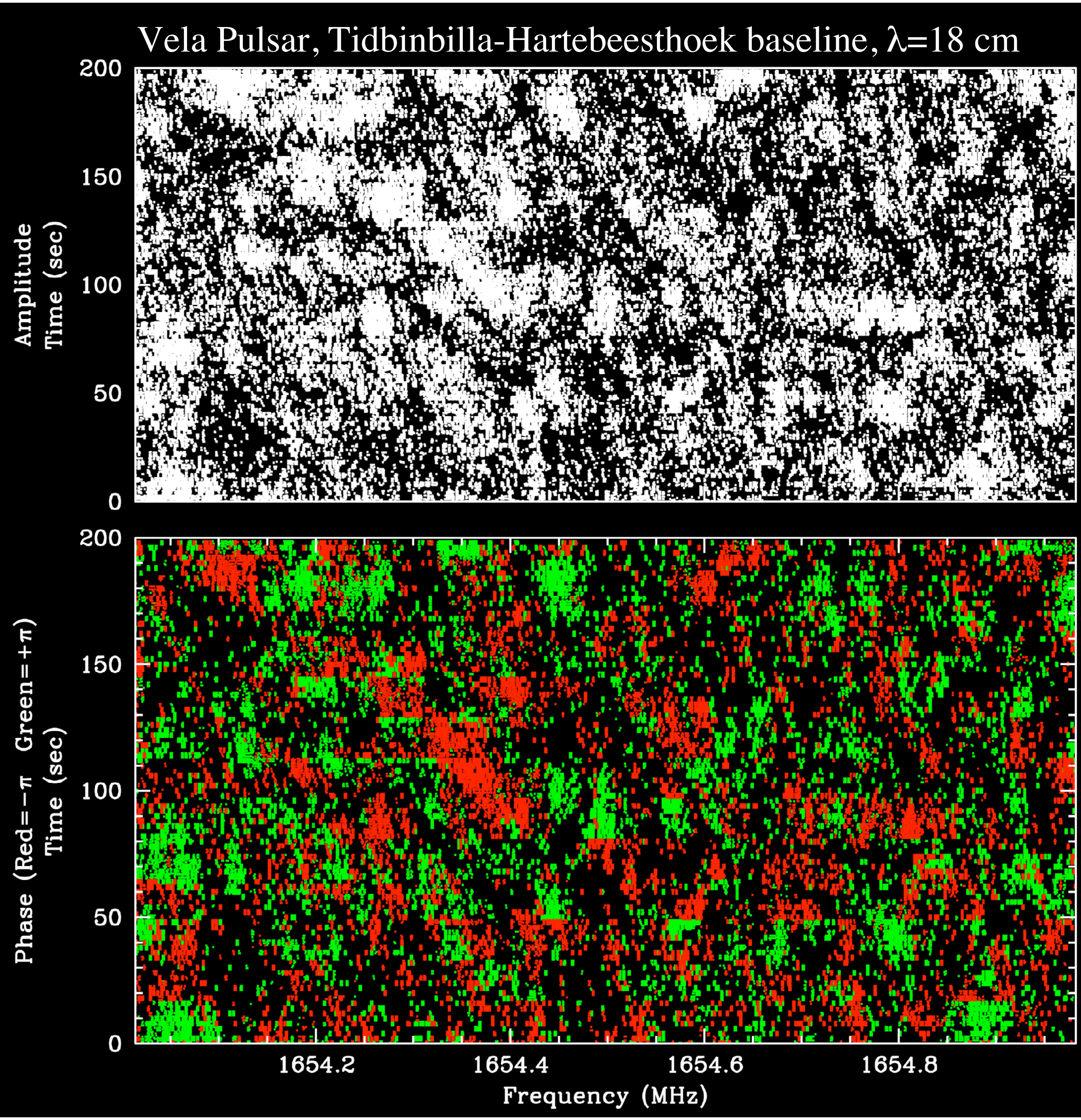
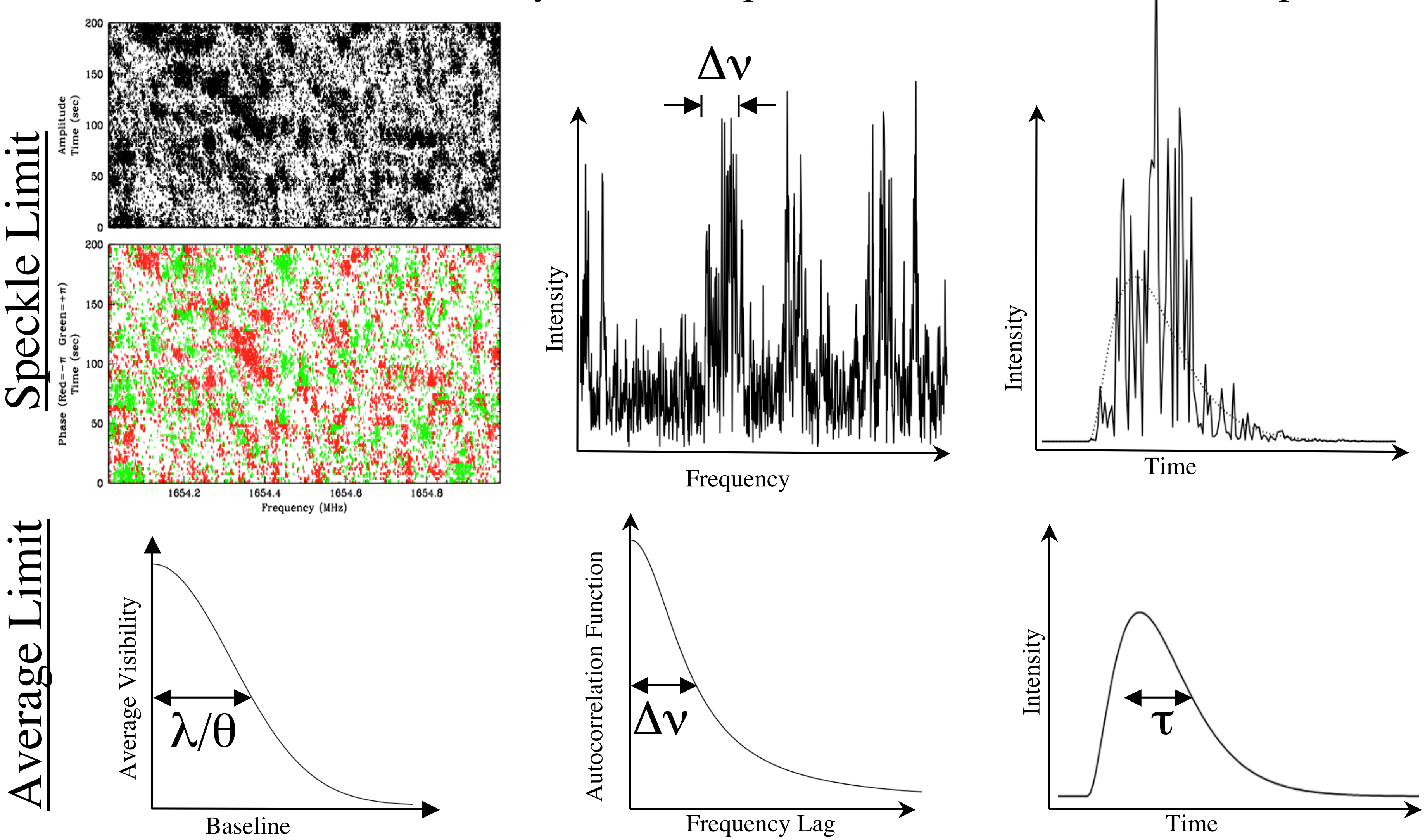
Interferometer sees amplitude changes with time and frequency, and phase changes if the antennas are far apart relative to the speckle size.



Vela Pulsar, Tidbinbilla-Hartebeesthoek baseline, λ=18 cm

Speckle -vs- Average-Image Limits

Interferometric Visibility | Spectrum | Pulse Shape

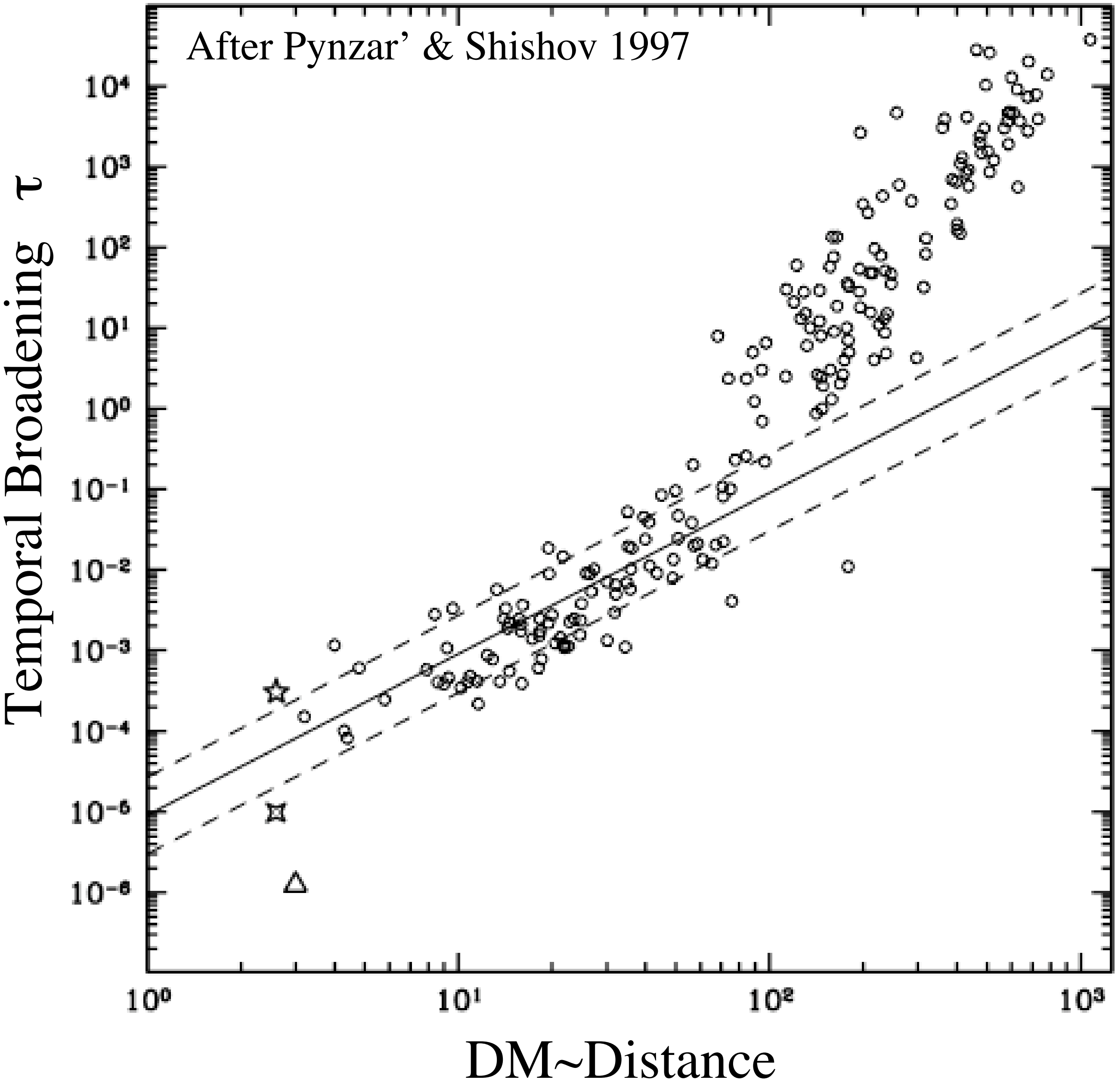


Closer pulsars tend to be less heavily scattered, with smaller scattering disk angle θ, larger bandwidth Δν, and shorter temporal broadening τ. Nearby pulsars are usually seen in the speckle limit.

Distribution of Scattering Material

τ-DM Scaling differs for Nearby and Distant ISM

Break in power-law suggests:
-nearby scattering is uniform,
-distant scattering is clumpy.

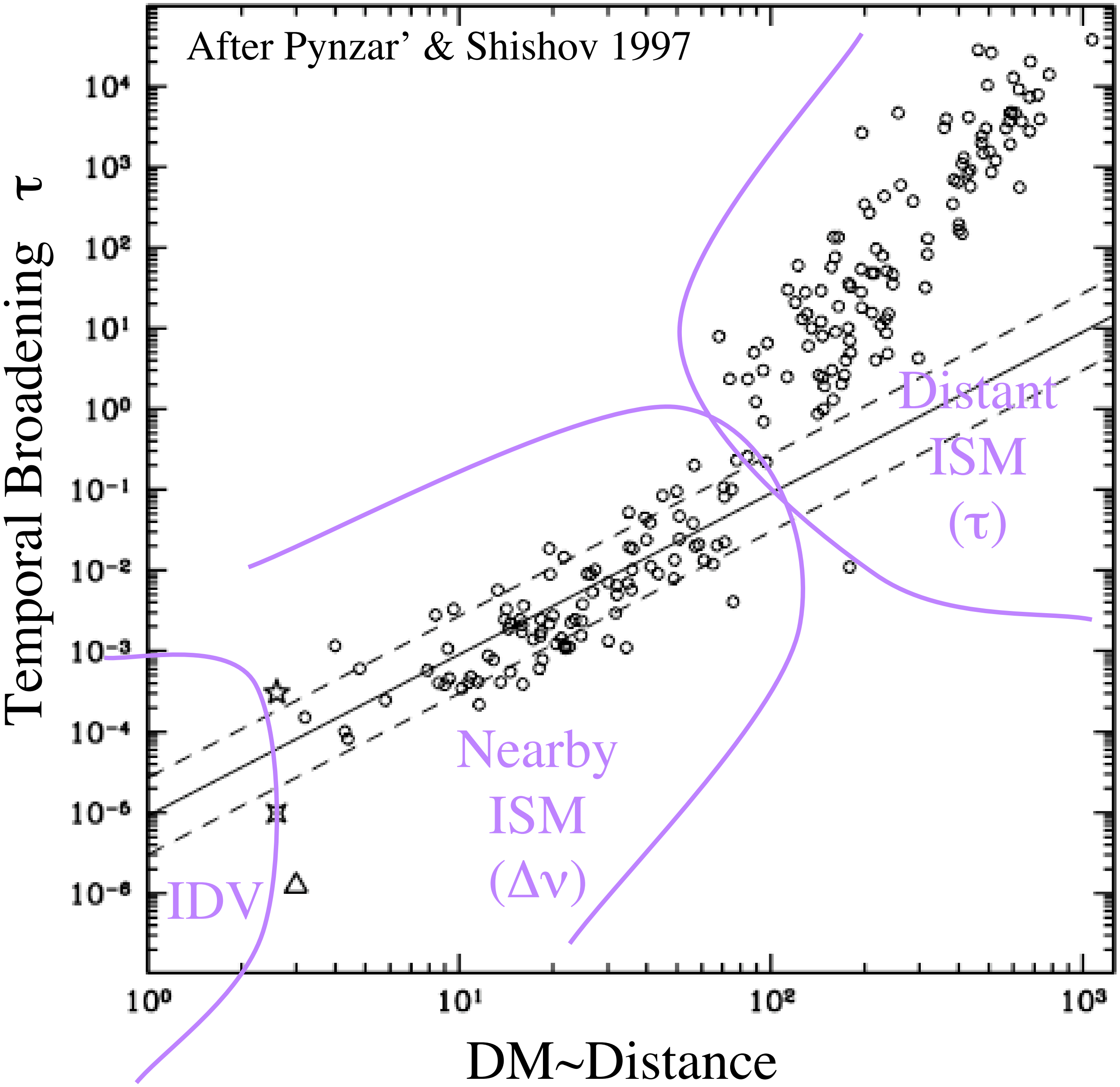


τ-DM Scaling differs for Nearby and Distant ISM

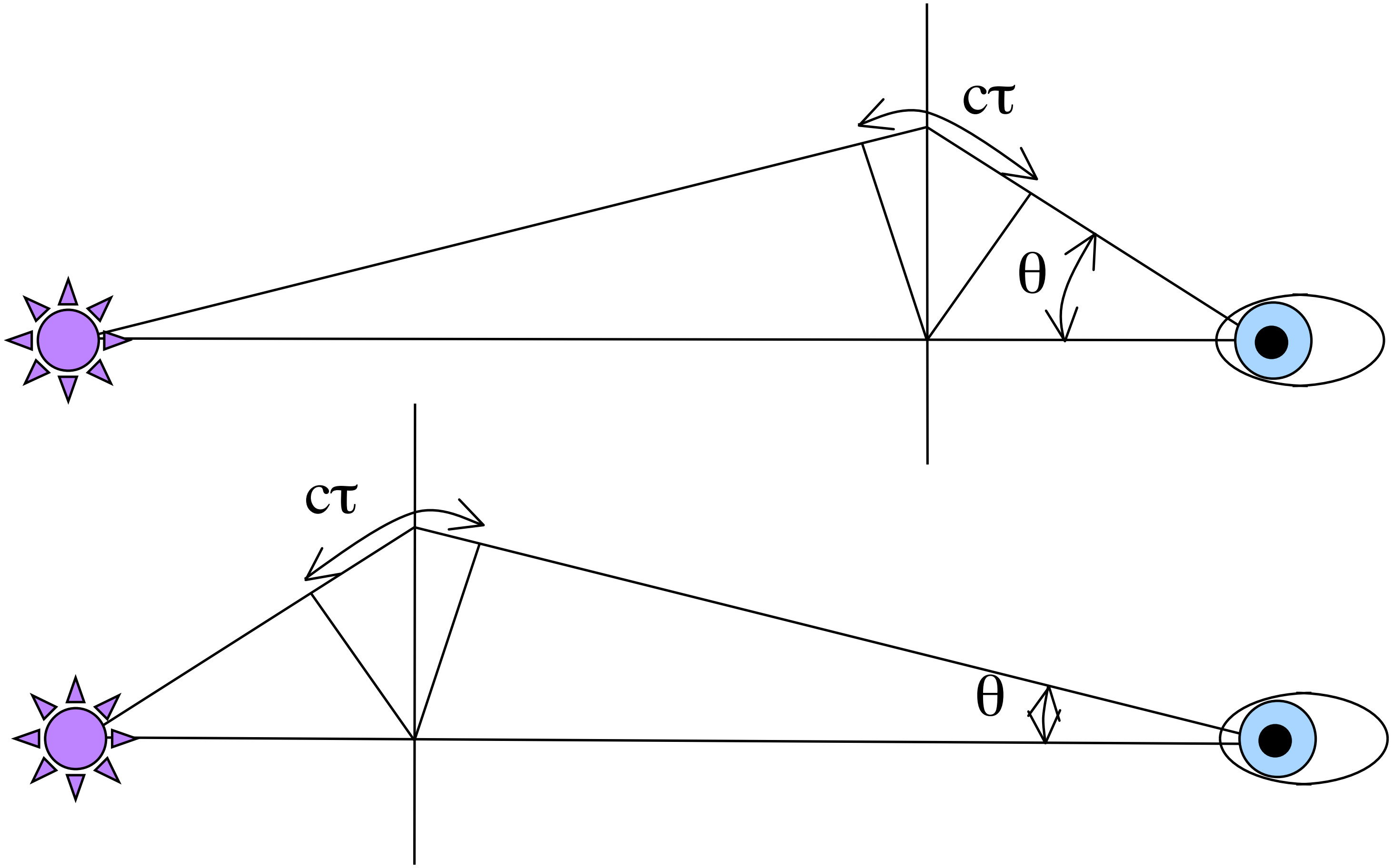
Break in power-law suggests:
-nearby scattering is uniform,
-distant scattering is clumpy.

For nearby pulsars, τ must be estimated from Δν in the speckle limit:

$$\Delta\nu \approx 1/2\pi\,\tau.$$

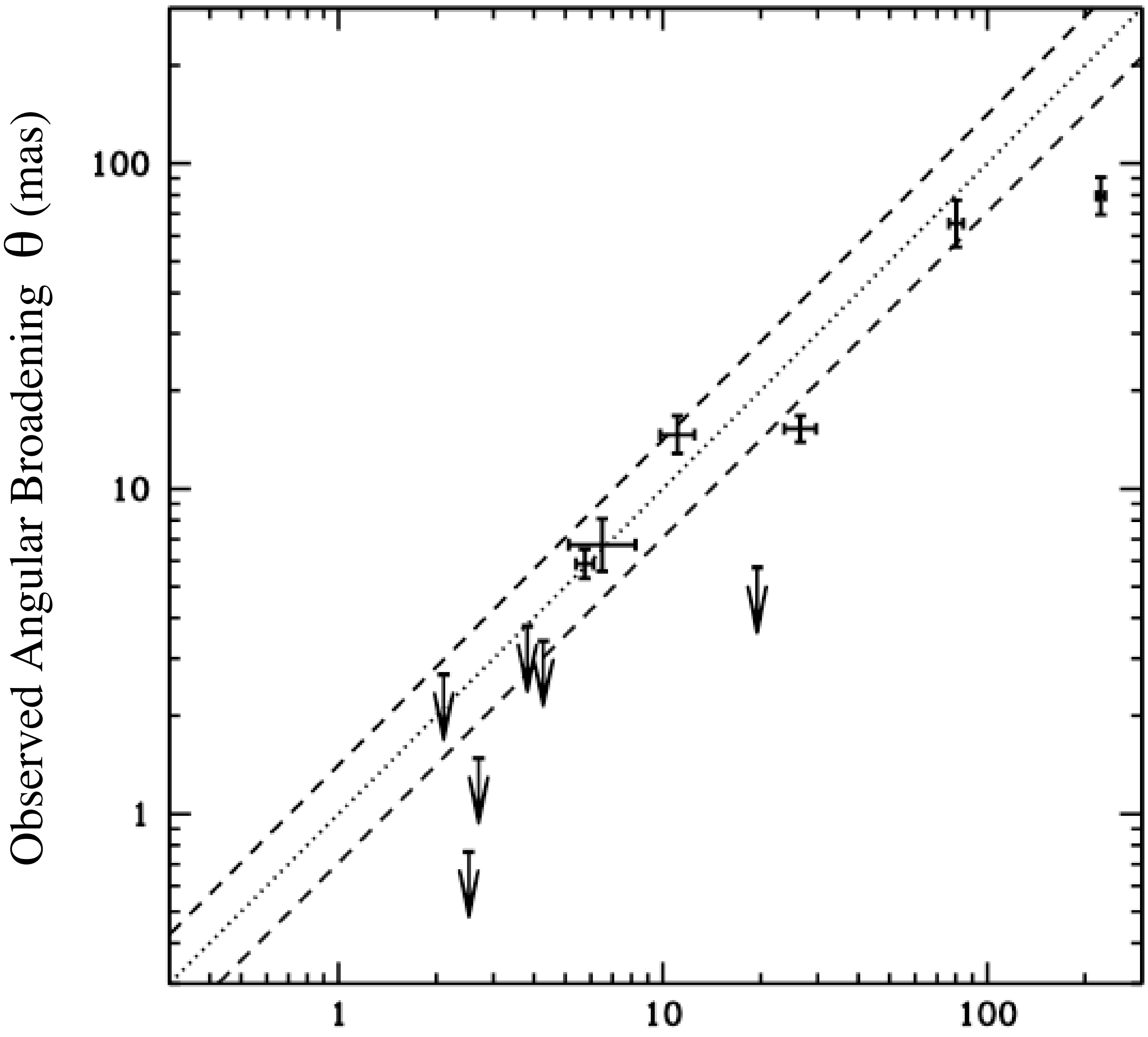


Angular broadening θ is *larger* (relative to temporal broadening cτ) when scattering material is *closer* to the observer



In principle, comparison of θ and cτ yields the distance to scattering screen.

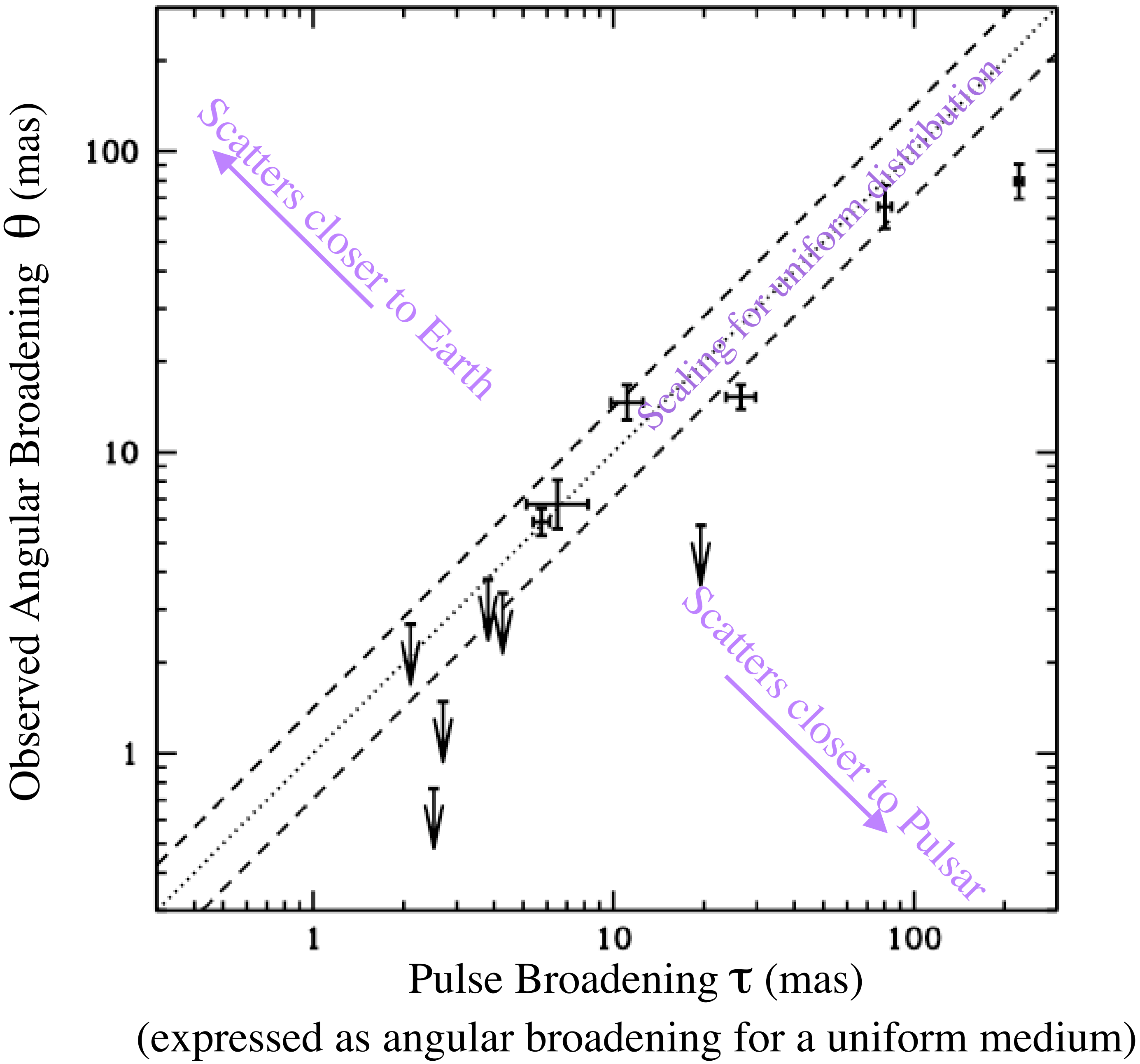
From: Britton 1998



Pulse Broadening τ (mas)

(expressed as angular broadening for a uniform medium)

From: Britton 1998



Paradox:

The measured $\tau - \theta$ relation suggests:

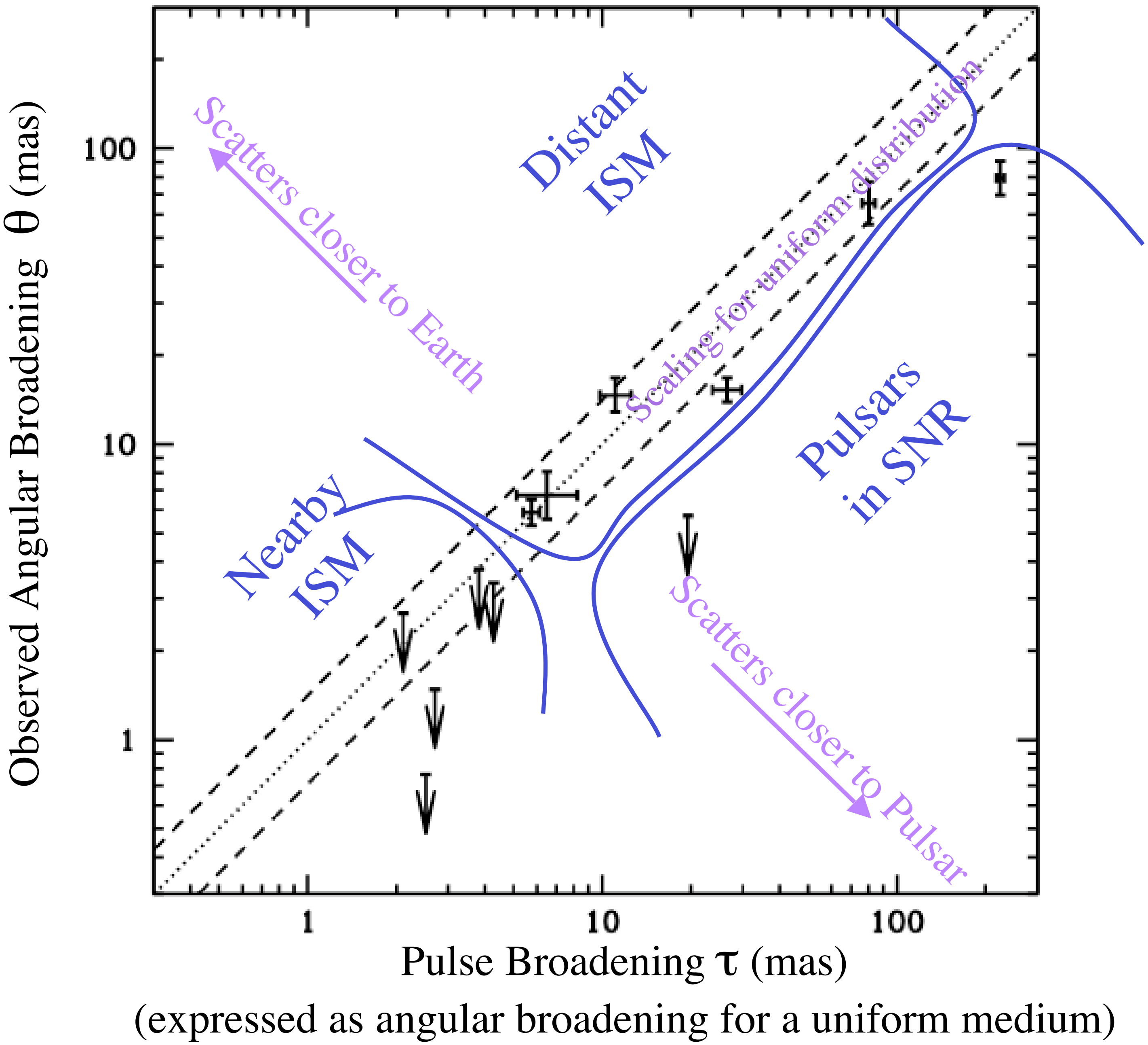
-SNR scatter pulsars inside;

-*distant* scattering is uniform;

-*nearby* scattering is clumped.

This is *opposite* the usual picture.

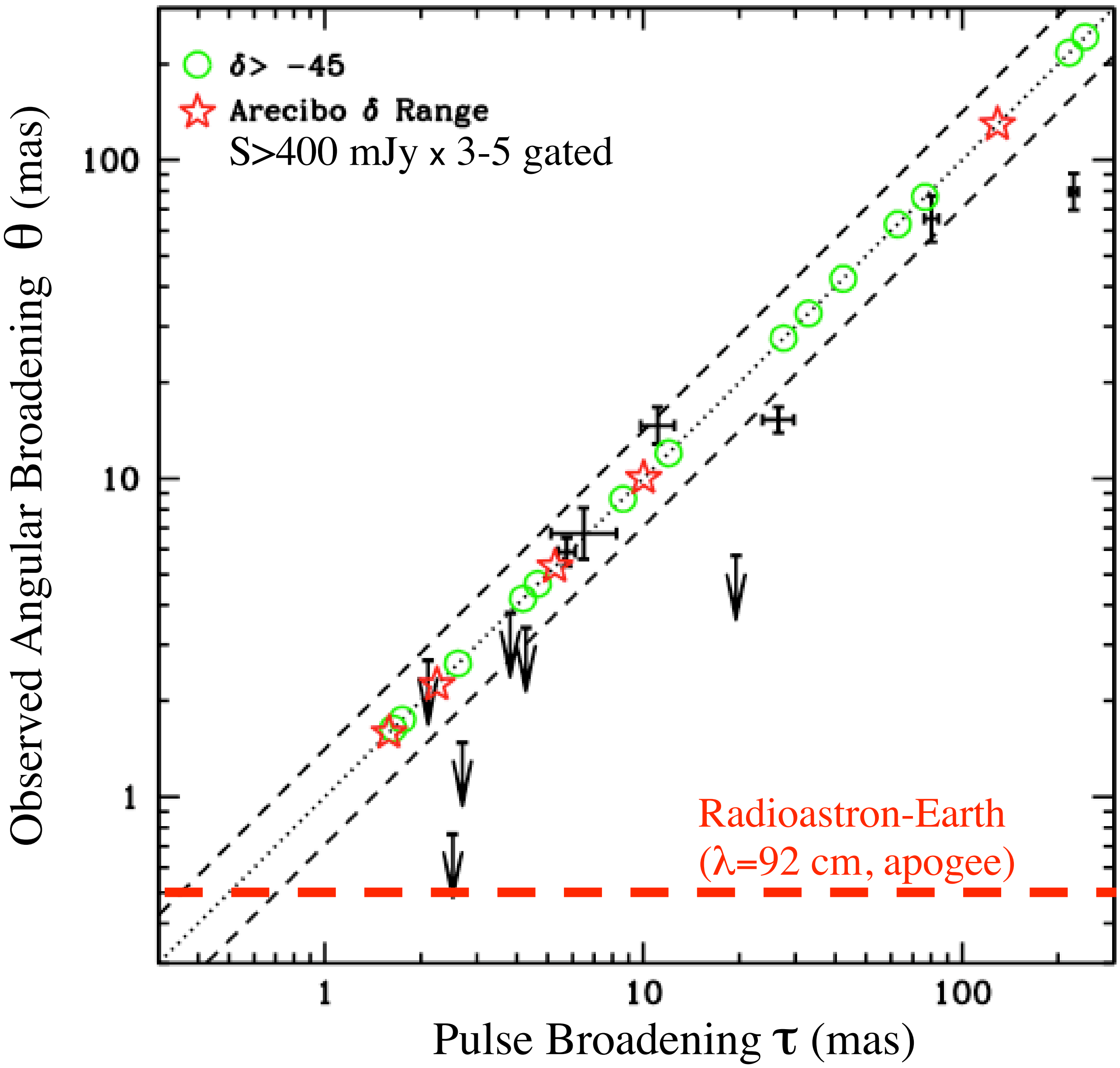
From: Britton 1998



Radioastron

Can measure θ’s reliably for many nearby pulsars--

and so improve understanding of the distribution of nearby scattering material.



(expressed as angular broadening for a uniform medium)

Shapes of Scattering Disks

Simple theory says: Scattering smooths images

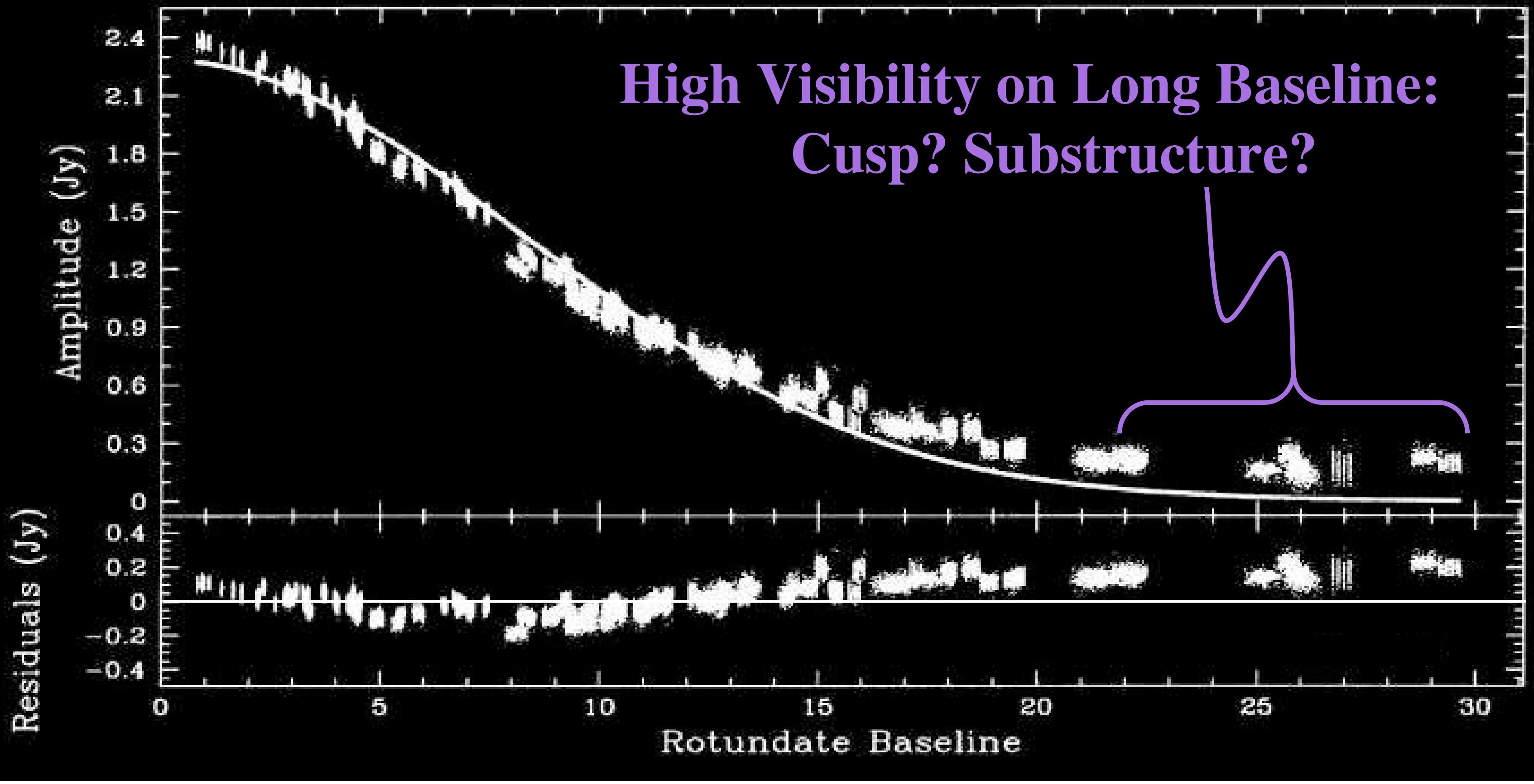
- Deflections resemble a random walk
- Theory predicts nearly* Gaussian distribution of intensity

  *Important correction from V. Kolmgorov

Some observations say: not completely

- Elevated visibility at long baseline

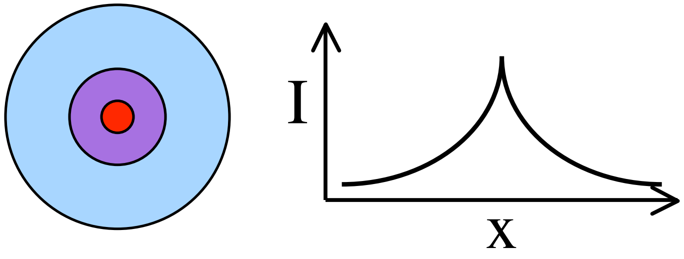
Desai & Fey ApJ 2001



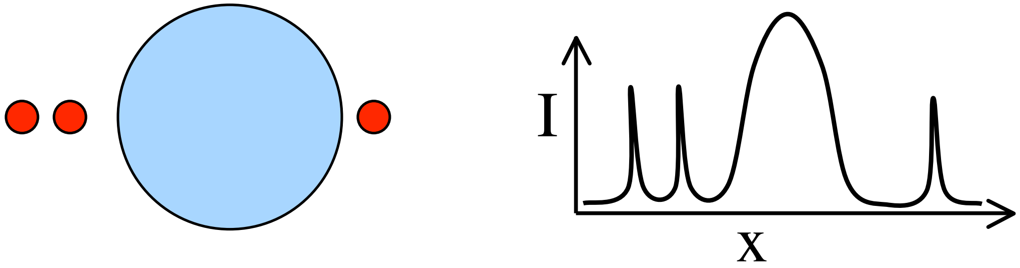
High Visibility on Long Baseline: Cusp? Substructure?

Theoretical Pictures May Explain Non-Gaussian Structure

- Cusps from non-Gaussian statistics?
  - Levy flights? (Boldyrev & Gwinn 2003,…)



- Subimaging from small-scale structure in the ISM?
  - Parabolic scintillation arcs? (Stinebring 2001,…)
    - (See V. Shishov talk)



Suggested Observational Test:

Resolve pulsar scattering disks using Radioastron.

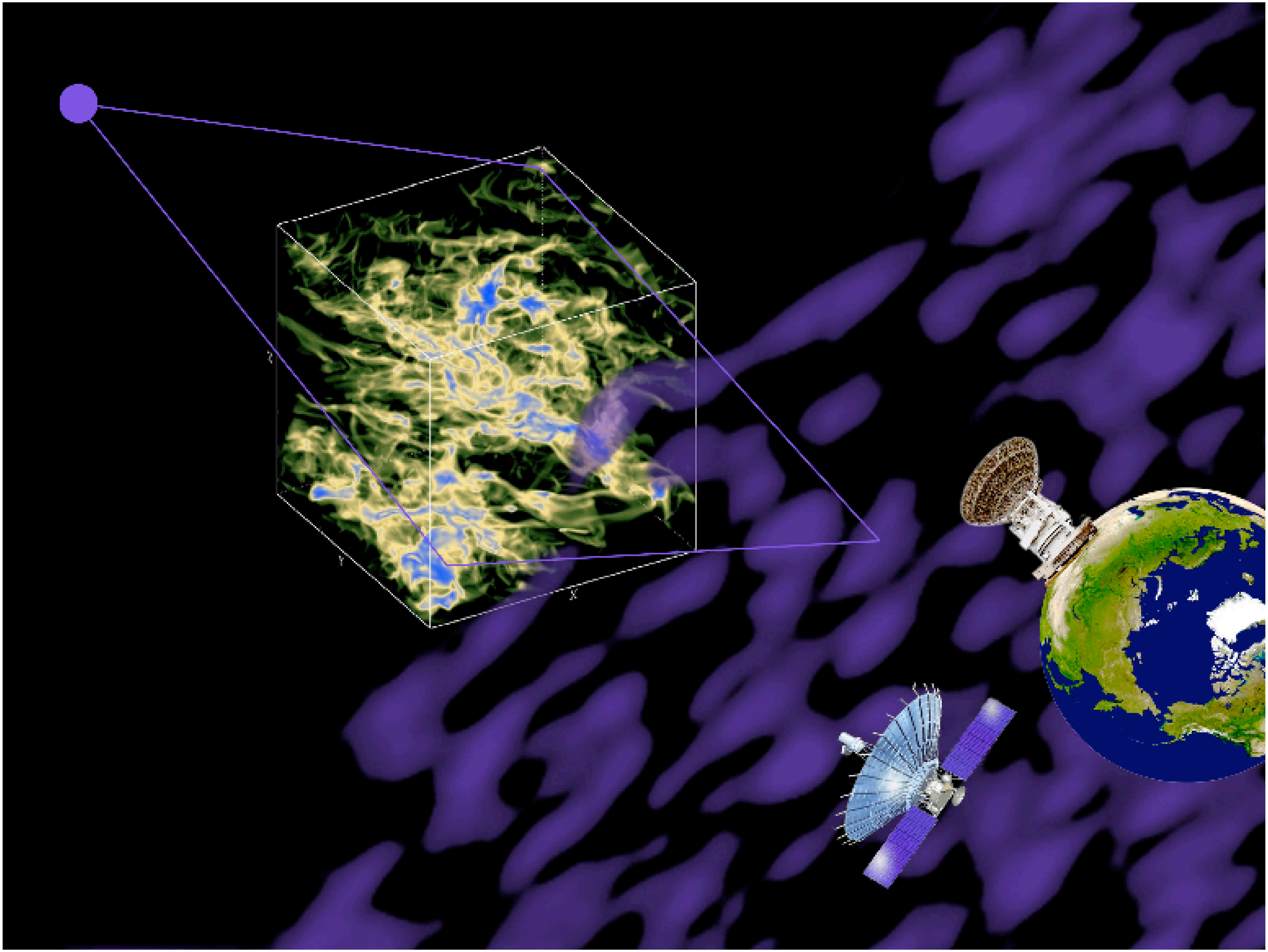
–Pulsars: intrinsically very small

–Radioastron: Baselines are long enough to explore small-scale structure

Structures
of Pulsar Emission Regions

Structure of Pulsar Emission Regions

- Scattering acts as a lens to form a corrupt image of the source in the observer plane: the speckle pattern
- Finite source size affects the distribution of observed scintillations: we can measure source size and shape!
- Accurate understanding of noise is critical to setting limits on, or measuring, size (and shape?) of the source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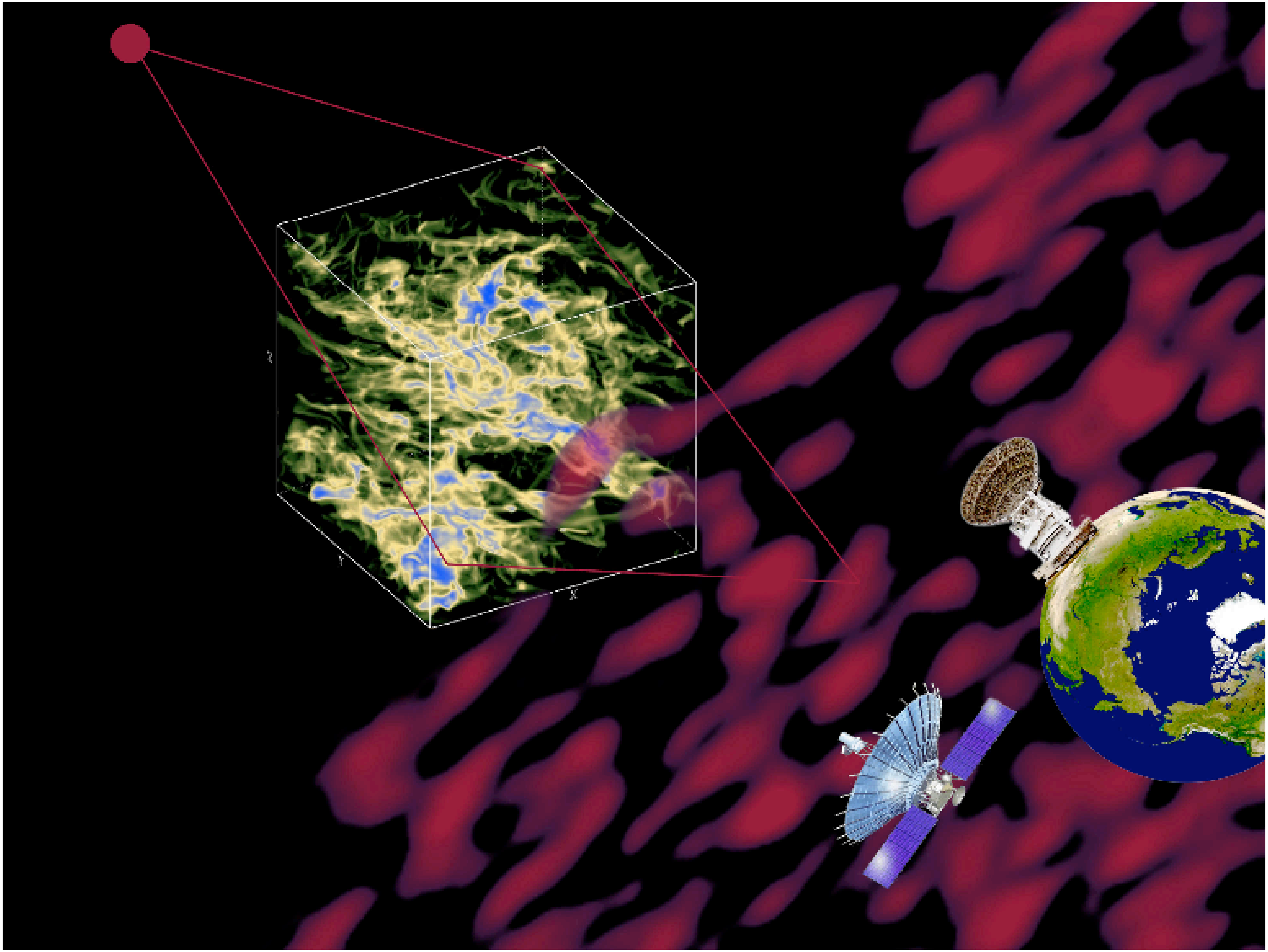
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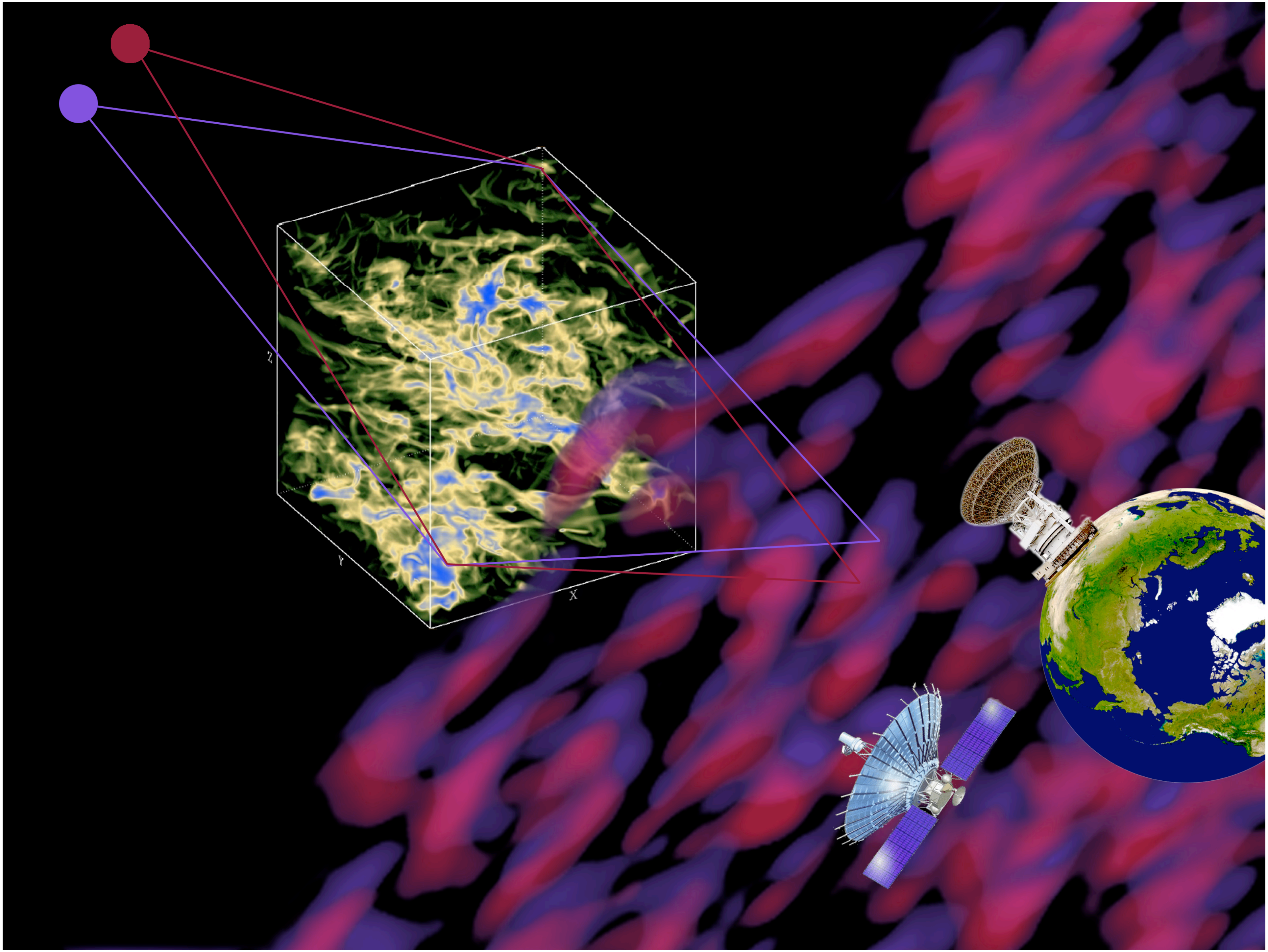
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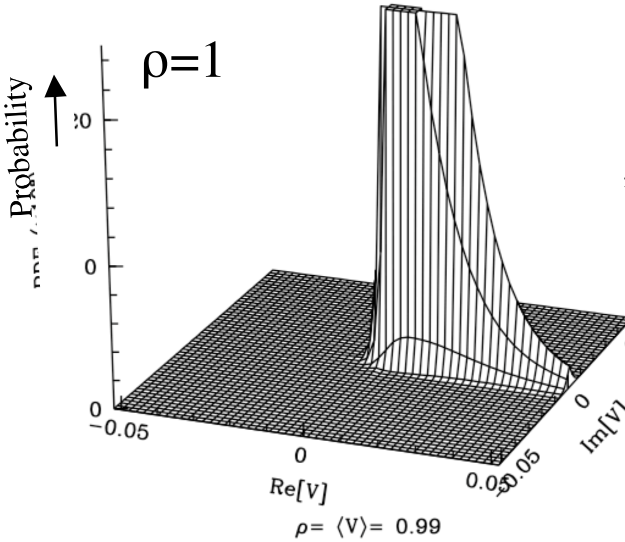
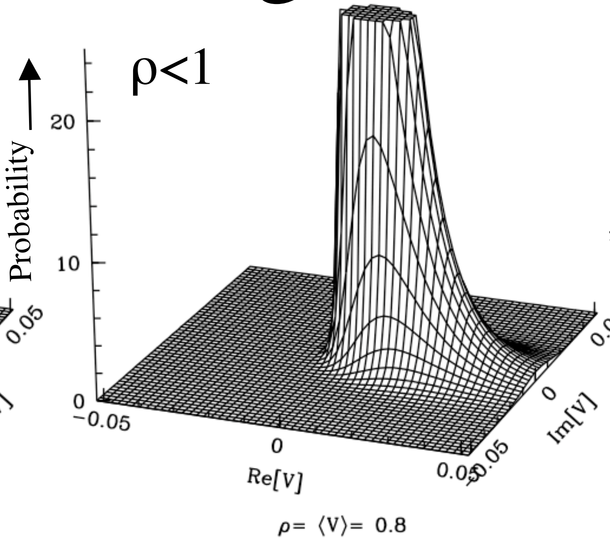
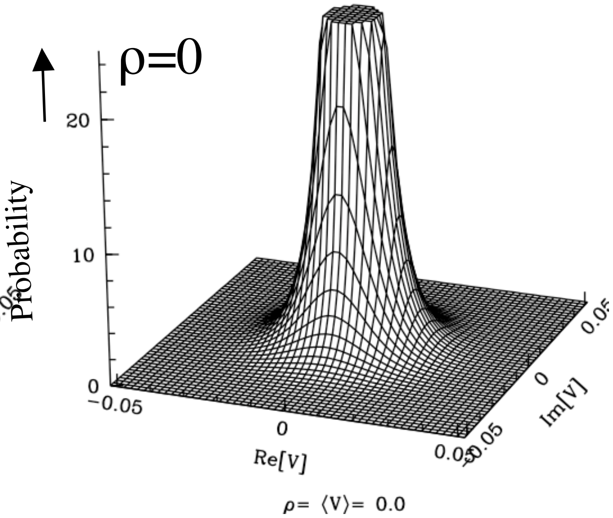
Distribution of Visibility for a Scintillating Point Source



Zero Baseline



Short Baseline



Long Baseline

For 0 baseline, the distribution of visibility is exponential along Re[V] (=distribution of intensity for a single dish).

As the baseline lengthens, the distribution broadens in Im[V].

$$P(V) = \frac{1}{\pi(1-\rho^2)} K_0\left(\frac{1}{(1-\rho^2)}|V|\right) \exp\left(\frac{1}{(1-\rho^2)}\,\rho\,\mathrm{Re}[V]\right)$$

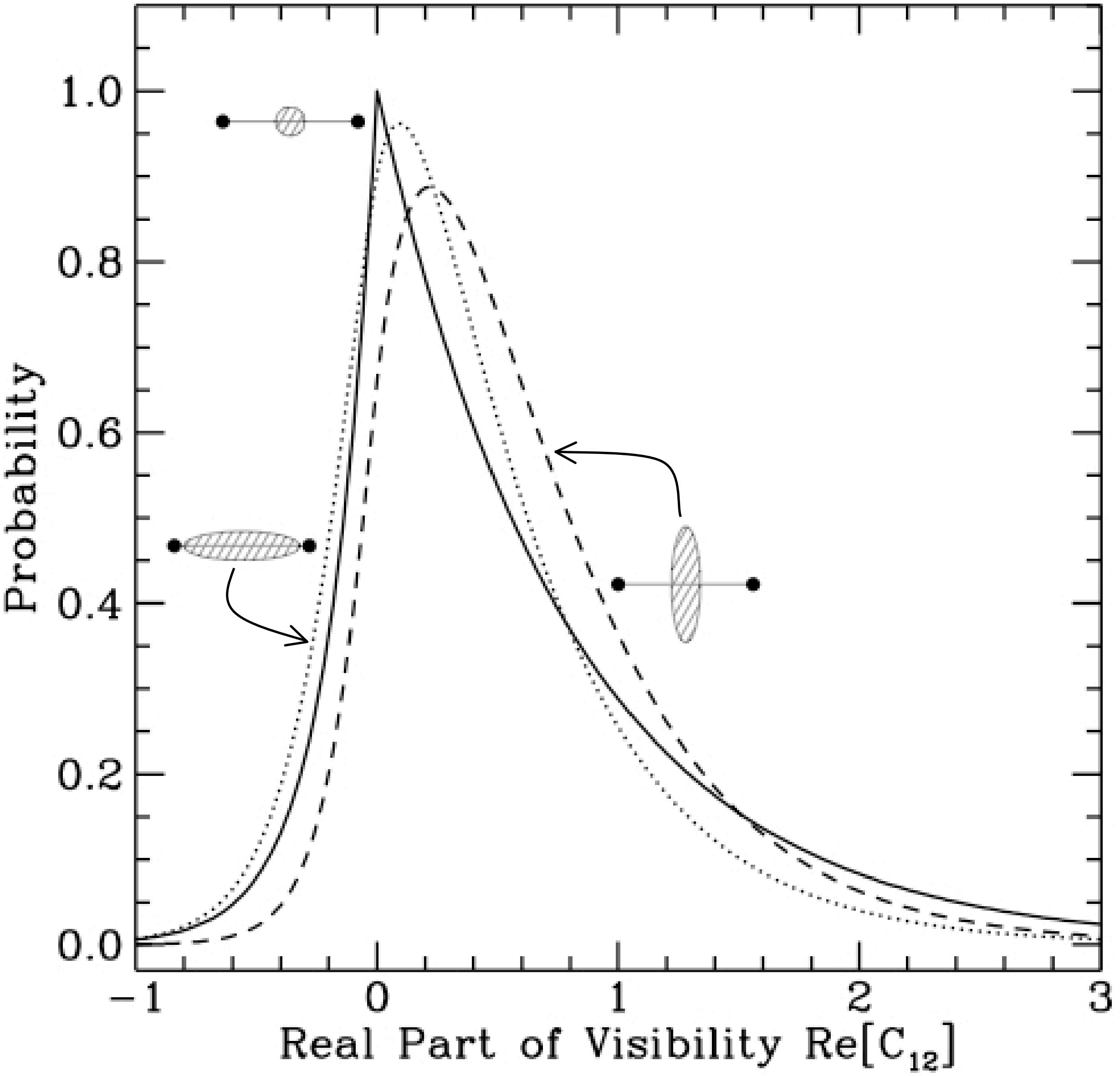
For long baselines, the distribution is circular (phase is random).

“Interferometric Visibility of a Scintillating Source” ApJ 2001, 1197

Stars Twinkle, Planets Don’t

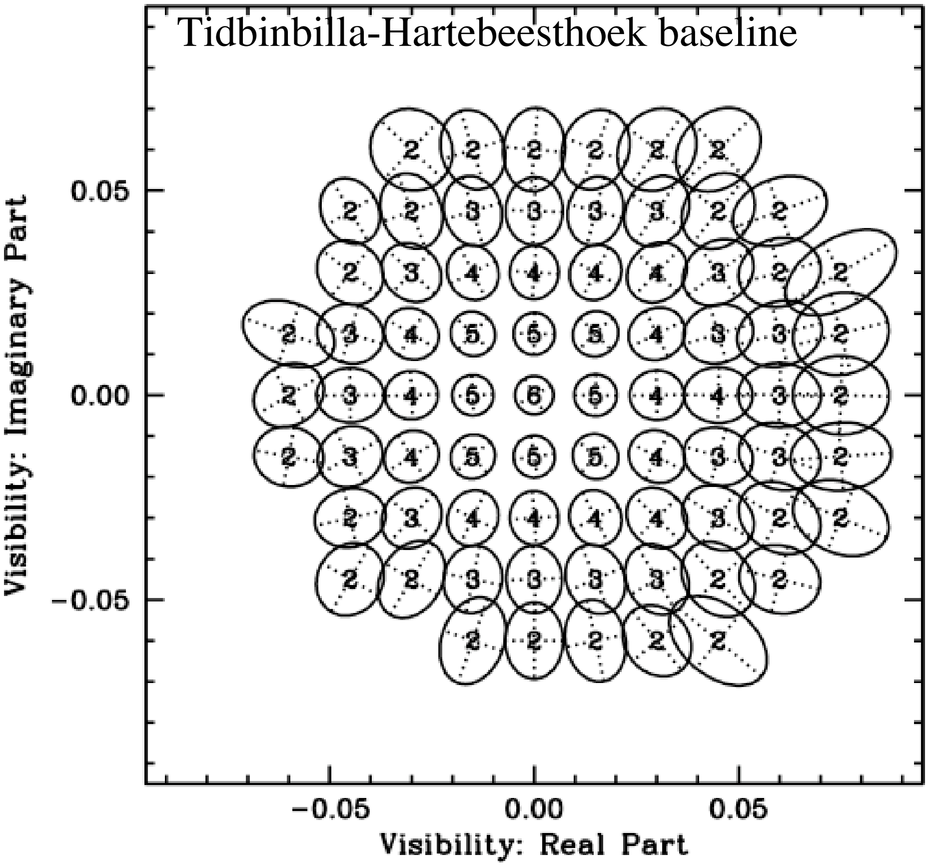
Extended source narrows the distribution of visbility and softens its sharp peak.

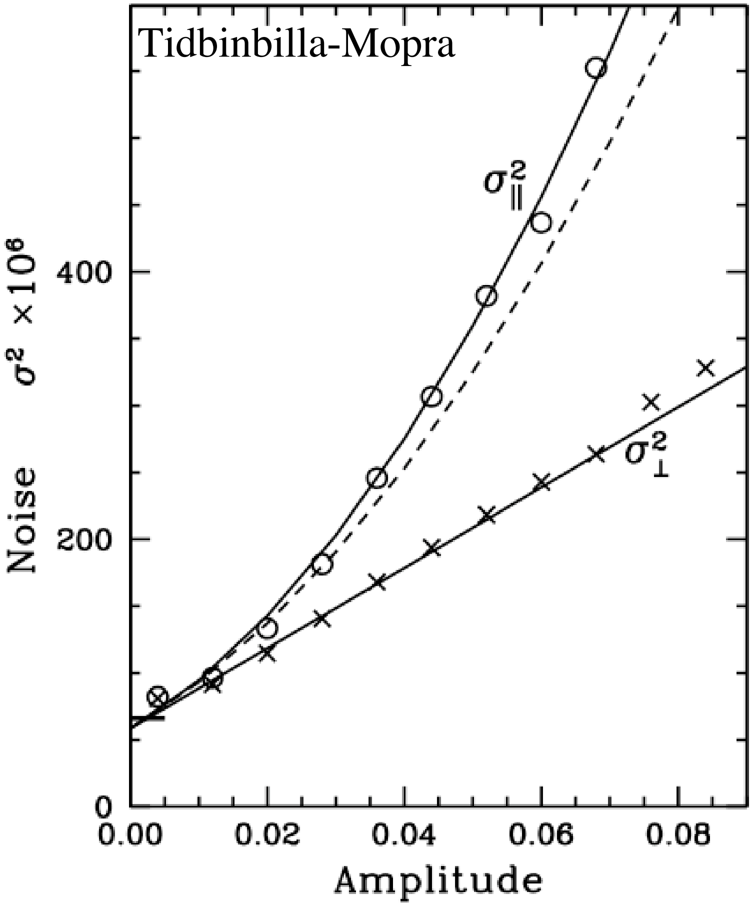
For a small, elliptical-Gaussian source: distribution of visibility is the convolution of 3 K_0·exp distributions.



Noise Affects the Observed Distribution

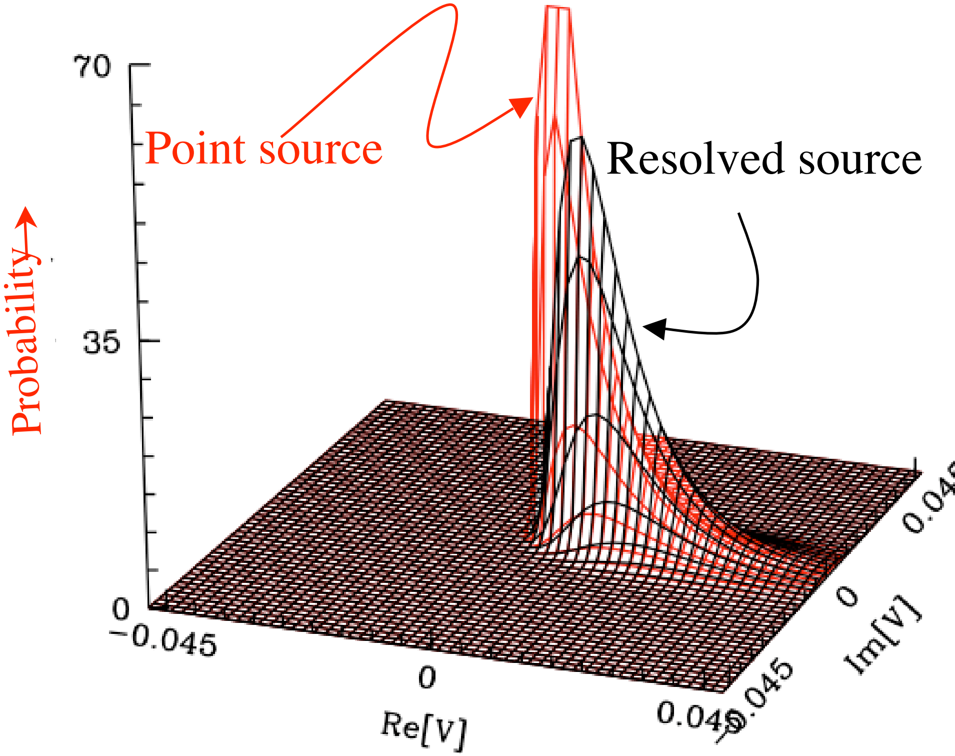
Noise includes source noise (self-noise),
which changes with intensity and visbility;
And sky, instrumental, and other noise,
which don’t.



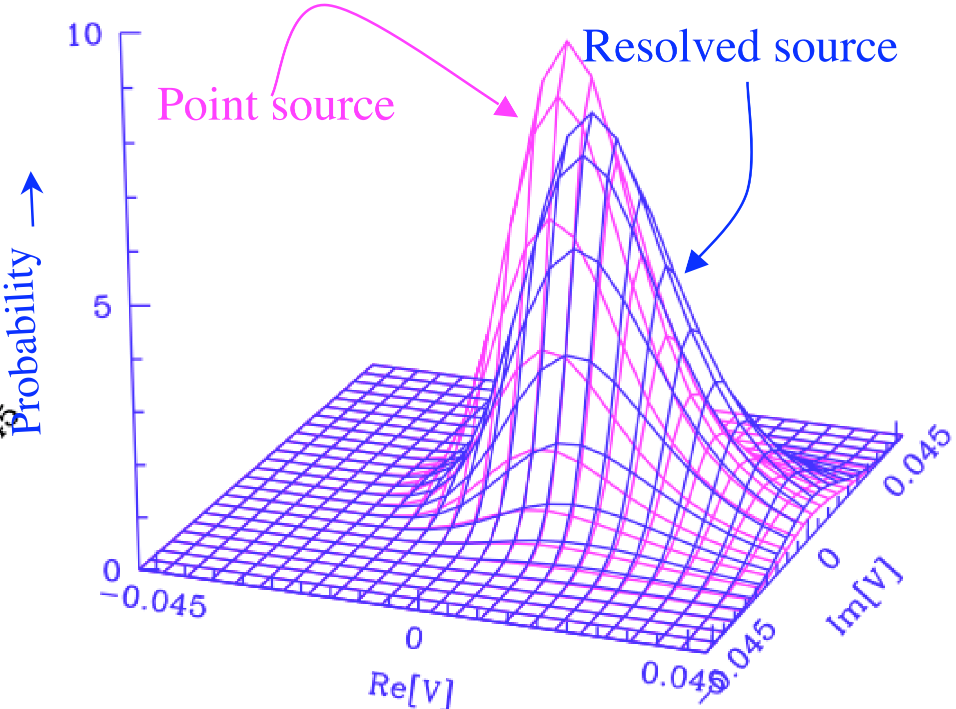


We assess all of the noise by comparing samples within one element of the scintillation pattern.

Effects of Source Structure+Noise



No Noise



With Noise (as Measured)

If the source is resolved, the peak is "softer", narrower, and shifted toward +Re[V]; the distribution is wider in Im[V].

Added instrumental and source noise soften the peak and widen the distribution, but do not shift it.

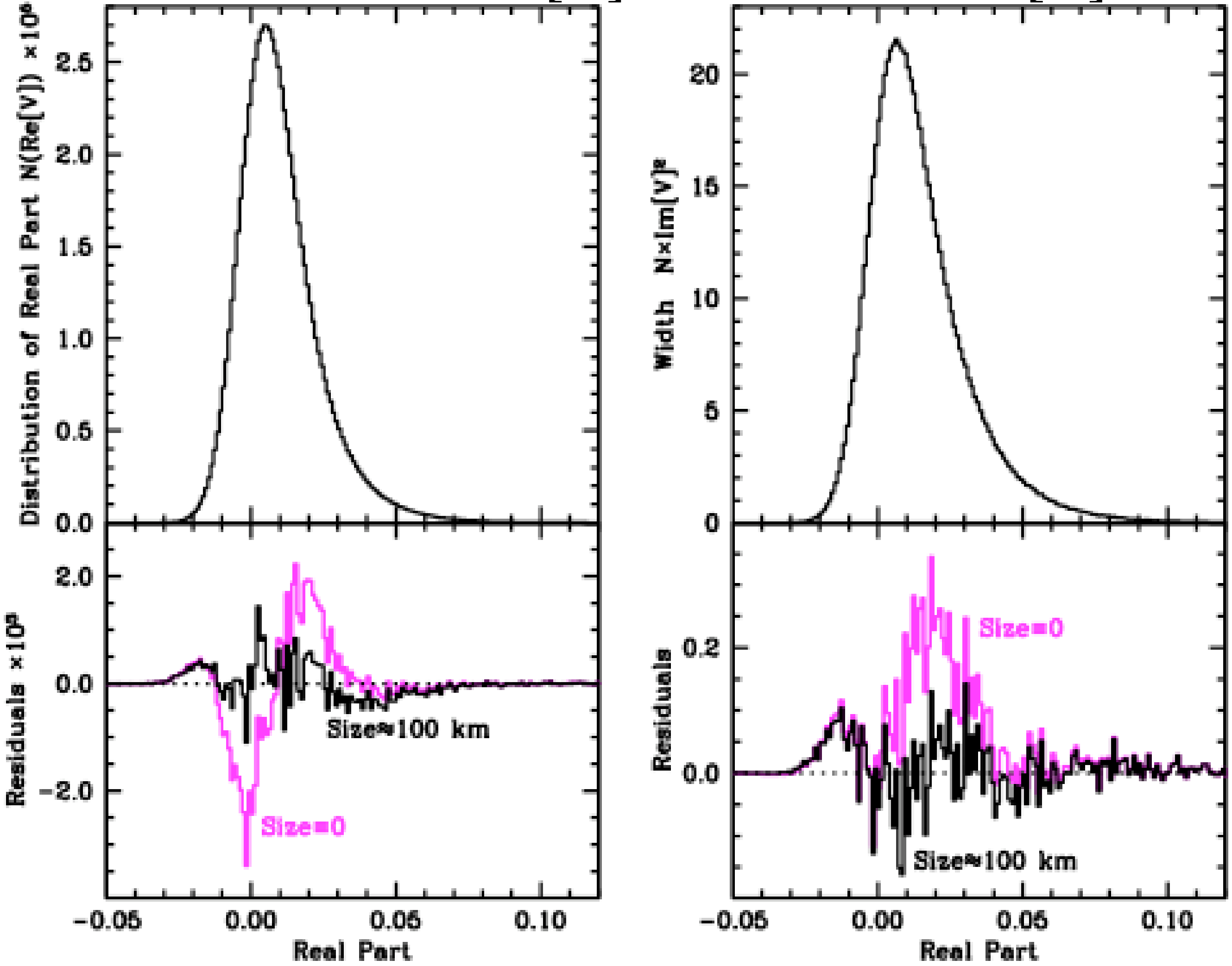
Fit a Model to the Data:

We fit simultaneously to the distribution projected onto bins along the real axis and to the mean square imaginary part in each bin.

Distribution of Re[V]

Width in Im[V]

Tidbinbilla-Mopra Baseline

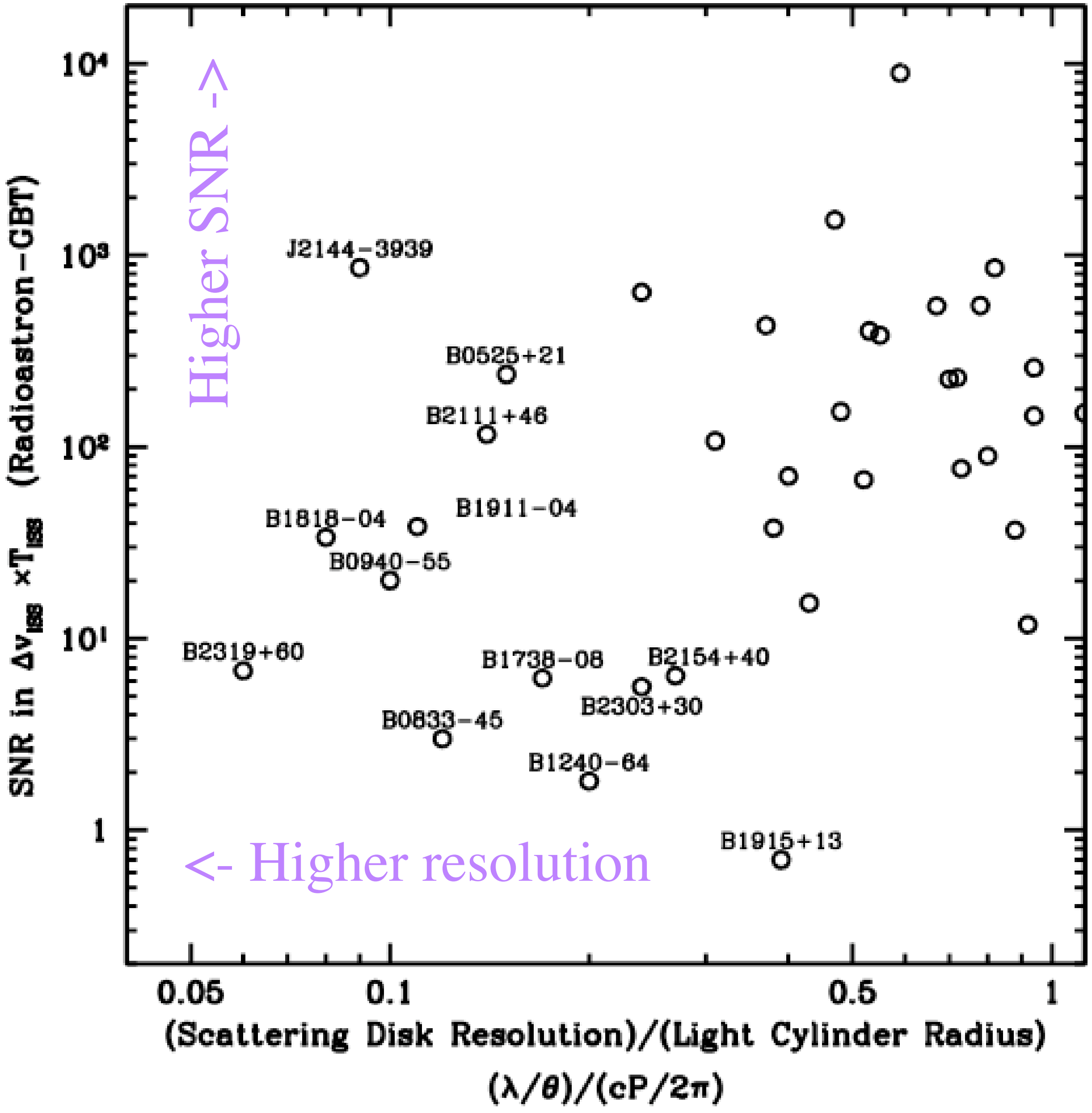


Sizes of Several Pulsars Are Accessible to Radioastron

Size measurement requires:

- High angular resolution by scattering disk
- Good SNR in one scintillation time and bandwidth
- Sufficient samples of scintillation in one observing session

λ=92 cm



Technical Factors

- Interference
- Recording & Correlation
  - Lag statistics

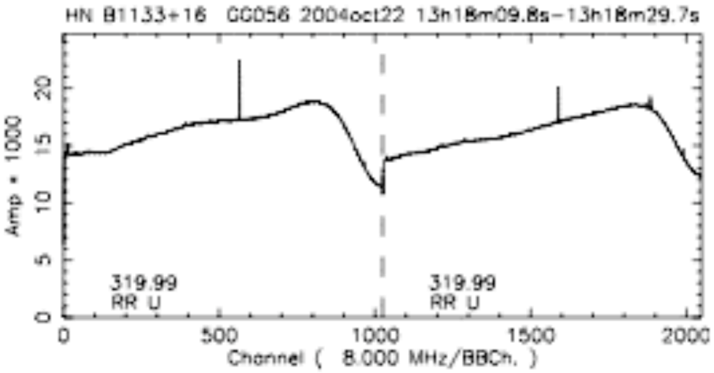
Interference

Are λ=92-cm observations feasible from interference standpoint?

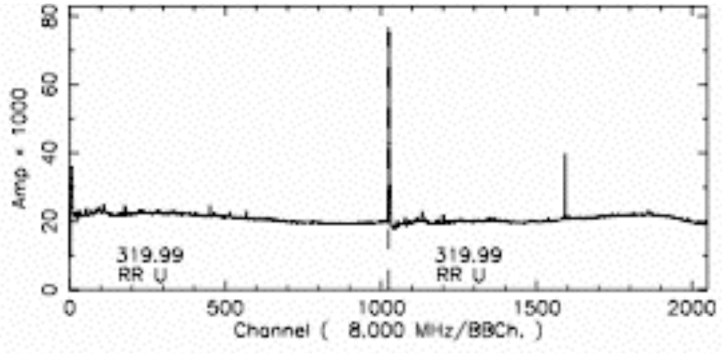
At λ=18-cm, interference environment is better, and similar science is accessible to Radioastron baselines.

λ=92-cm

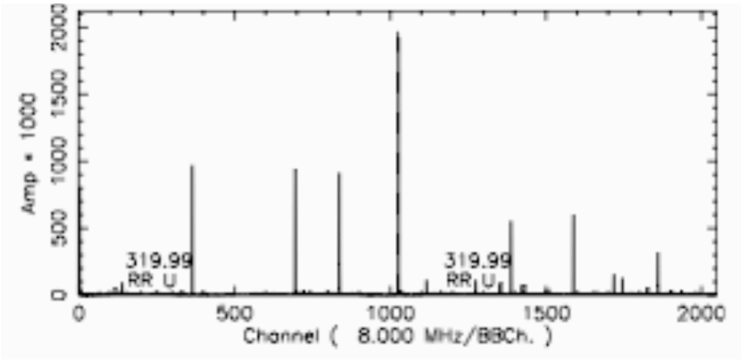
Excellent



Good



Not Good



For Useful Observations of Speckles Recorders and Correlator Must Possess:

- High spectral resolution
- Rapid writeout of spectra (lots of data!)
- Stable and well-documented statistics and noise

Challenges:

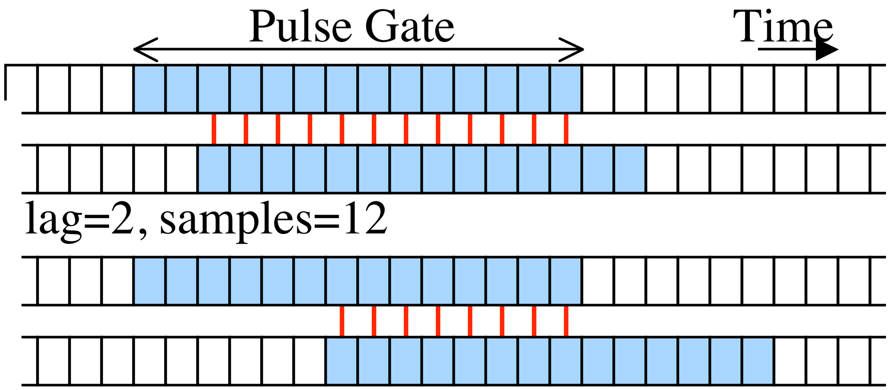
- Tsys varies over each pulsar pulse and with scintillation
  - effective quantizer levels vary
- Fractional bit-shift correction
  - rate may alias with pulsar period (!!)
  - (Integration time)=(N pulsar periods) -- can help
- “Wrap” assumption
  - noise may vary with lag

Prescription: Software correlator

Wrap Problem

Large Correlator Lags May Approach Width of Narrow Pulsar Gates

Larger Lags are Sampled Less than Smaller Lags

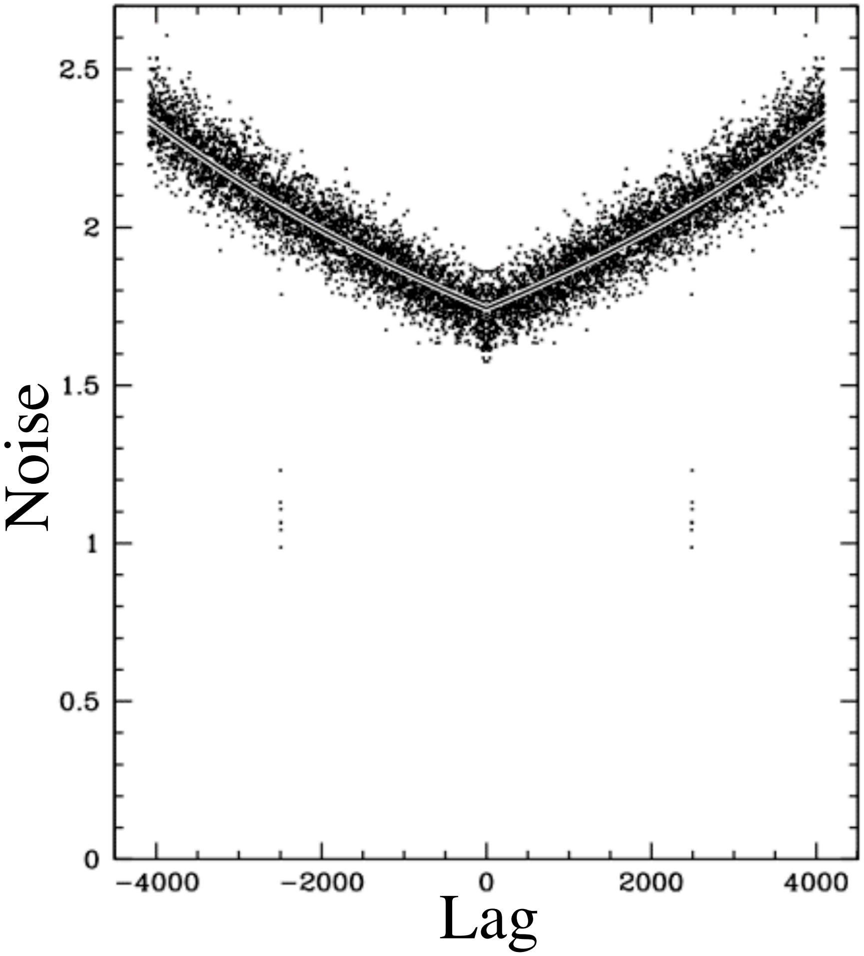


lag=2, samples=12

lag=6, samples=8

So: Higher Noise in Large Lags

So: Noise is correlated across spectrum



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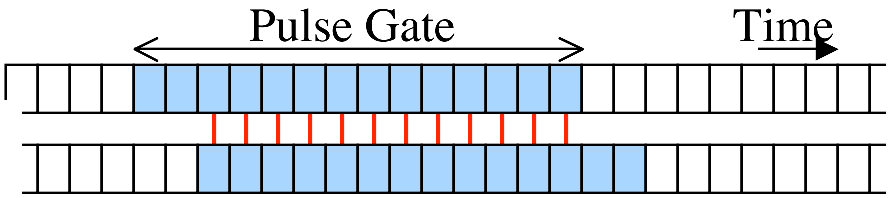
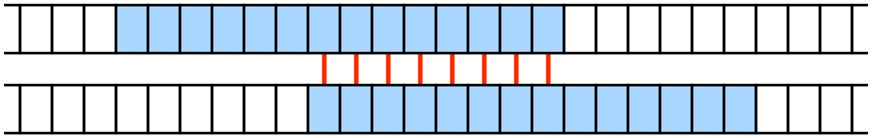


lag=2, samples=12



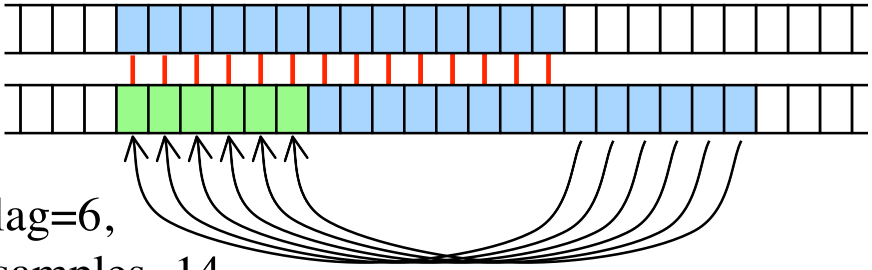
lag=6, samples=8

So: Higher Noise in Large Lags

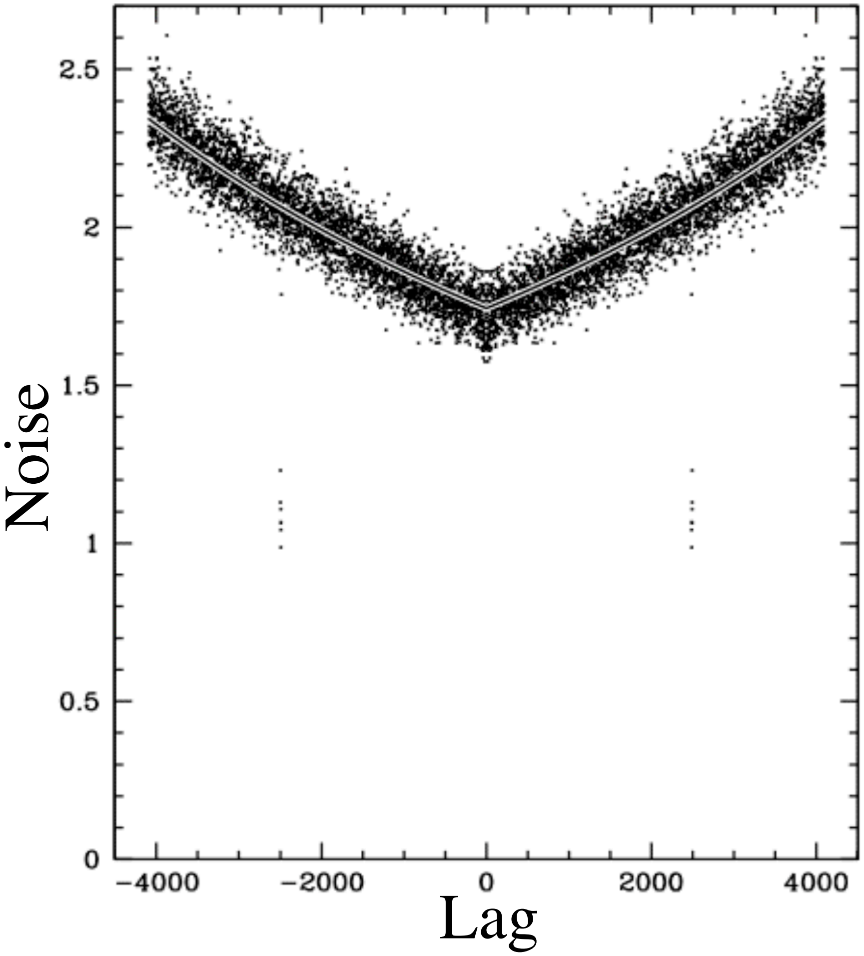
So: Noise is correlated across spectrum

Solution:**“Wrap” the lags.**

Recall: Fourier transform is circular!



lag=6,
samples=14



Summary

Pulsar VLBI is tricky, but can be rewarding!

Radioastron can provide unique observations of pulsars to help understand:

- distribution of scattering material
- cusps or substructure in scattering disks
- spatial structure of pulsar emission regions