VSOP-2 Observations of Pulsars

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Why VLBI of Pulsars?

- Astrometry
  - Parallax
  - Proper Motion
  - Cosmological Rotation
- Scattering
  - Interstellar Plasma Turbulence
  - Structure of Radio Pulsar Emission Region

VLBI of Pulsars with VSOP-2

- Pulsars are hard to observe
  - Weak at $\lambda < 20$ cm
  - Pulsed emission:
    - flux density is variable
    - Gating can increase SNR
- Scintillation complicates spectra
- Noise can be important

Astrometry: Cosmological Rotation

The local inertial reference frame is also the reference frame of the distant galaxies.

This isn’t the case for all model universes that are consistent with General Relativity.

Relative rotation of the frames can be measured using pulsar VLBI as an intermediary between the frames.

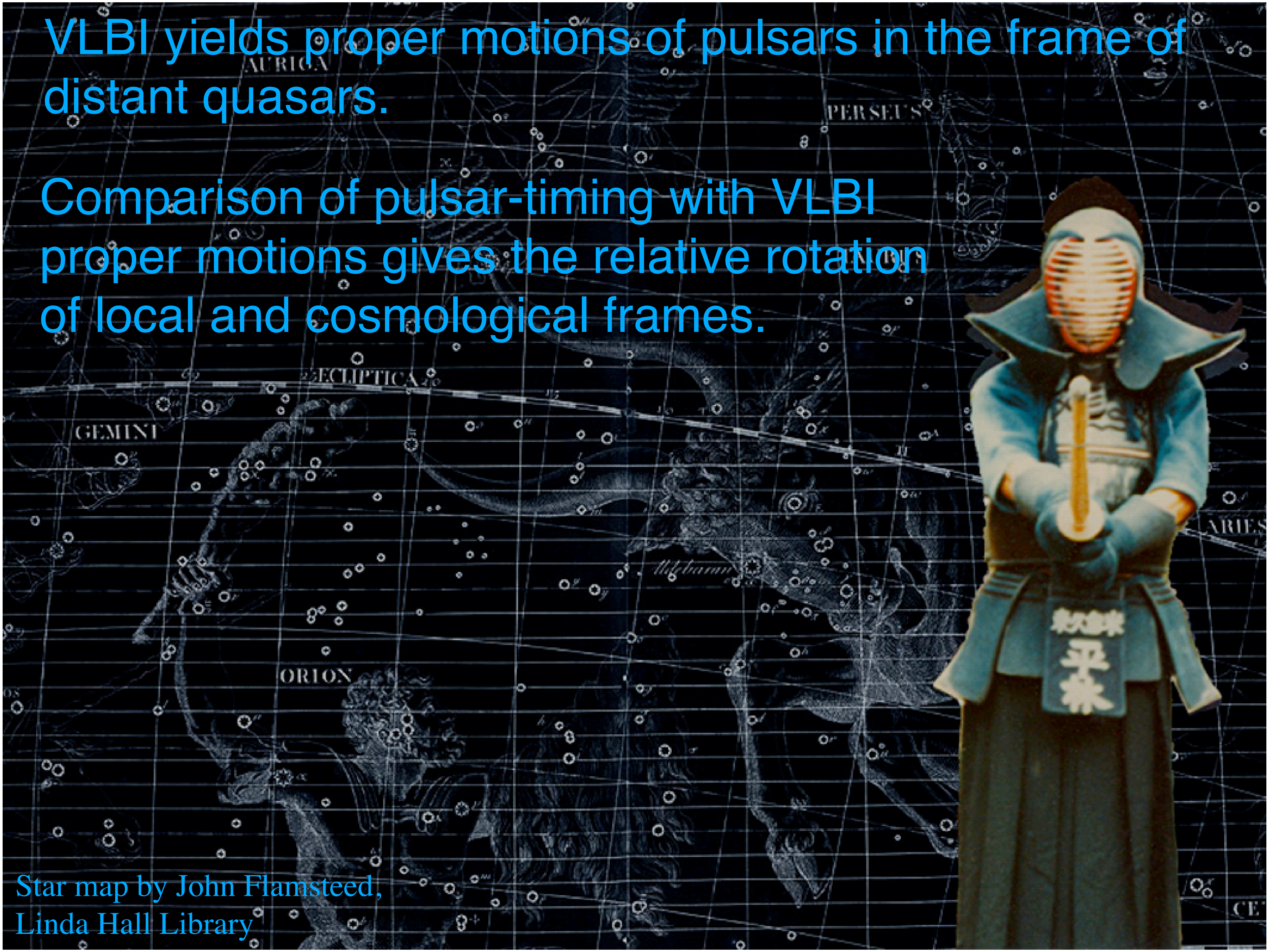

A room contains an ensemble of rotating, elastic spheres.
All have equatorial bulges except one. It is perfectly round.
That one is at rest, relative to the distant stars.
-- Sciama, The Physical Foundations of General Relativity

The Solar System acts as a gyroscope, with accurately-measured motions, understood via Classical Mechanics — in an inertial, non–rotating reference frame.

Timing of pulsars yields their proper motions in that frame.

VLBI yields proper motions of pulsars in the frame of distant quasars.

Comparison of pulsar-timing with VLBI proper motions gives the relative rotation of local and cosmological frames.



Star map by John Flamsteed,
Linda Hall Library

Some Numbers: PSR 0437-4715

- Flux density
  - 8 GHz: 16 mJy
  - 22 GHz: 2 mJy
- Accuracy of timing proper motion: ≈10 μas/yr
- Gain in SNR from Pulsar Gating: ×2.5

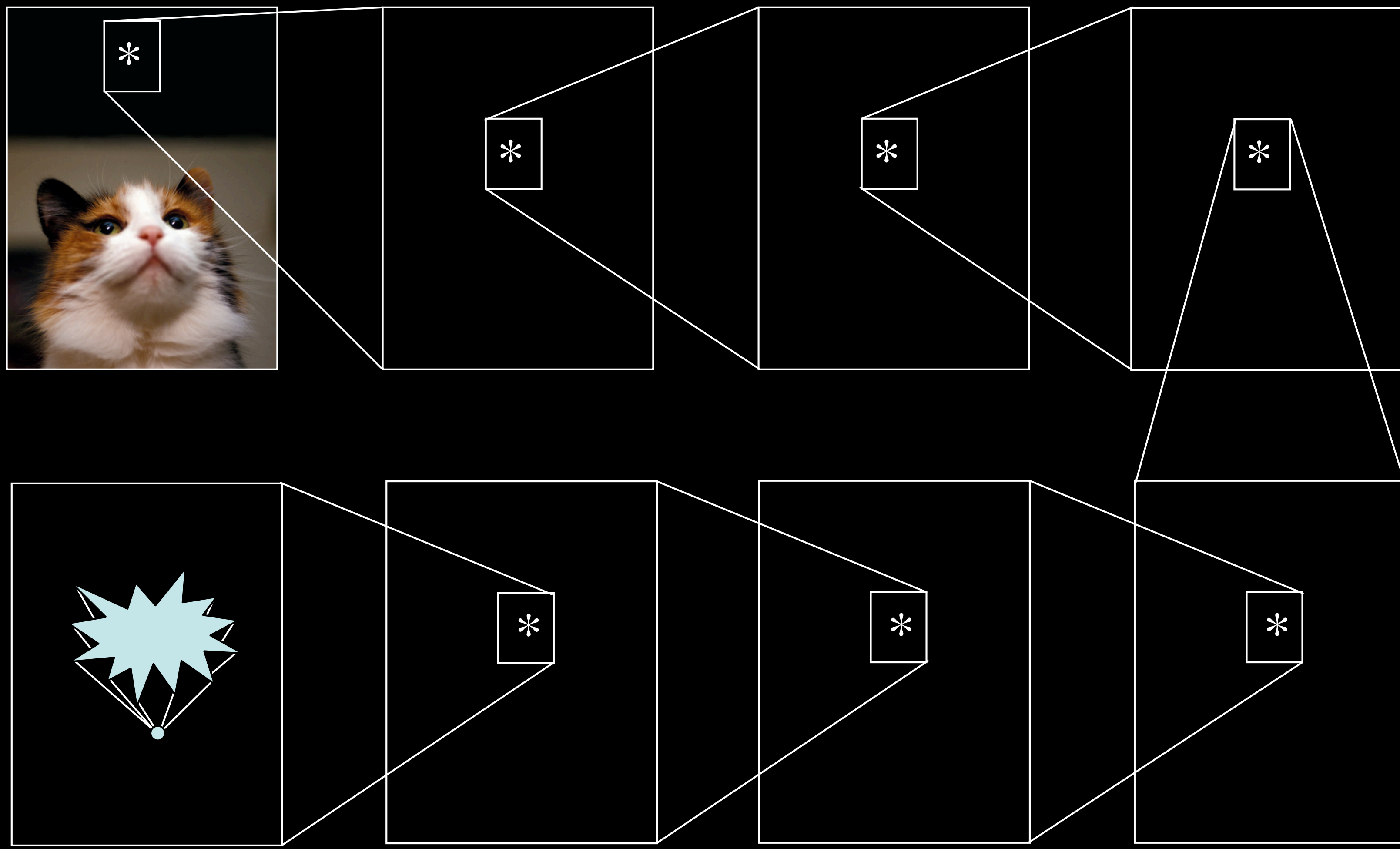
Scattering: Structure of Pulsar Emission Region

Scattering of radio waves in the interstellar plasma acts as a large, but very corrupt, lens.

This lens has a nominal resolution of about $\lambda/D\sim$100's of km, for some pulsars.

Pulsar VLBI allows measurement of the size of the emission region, if it is about this size.

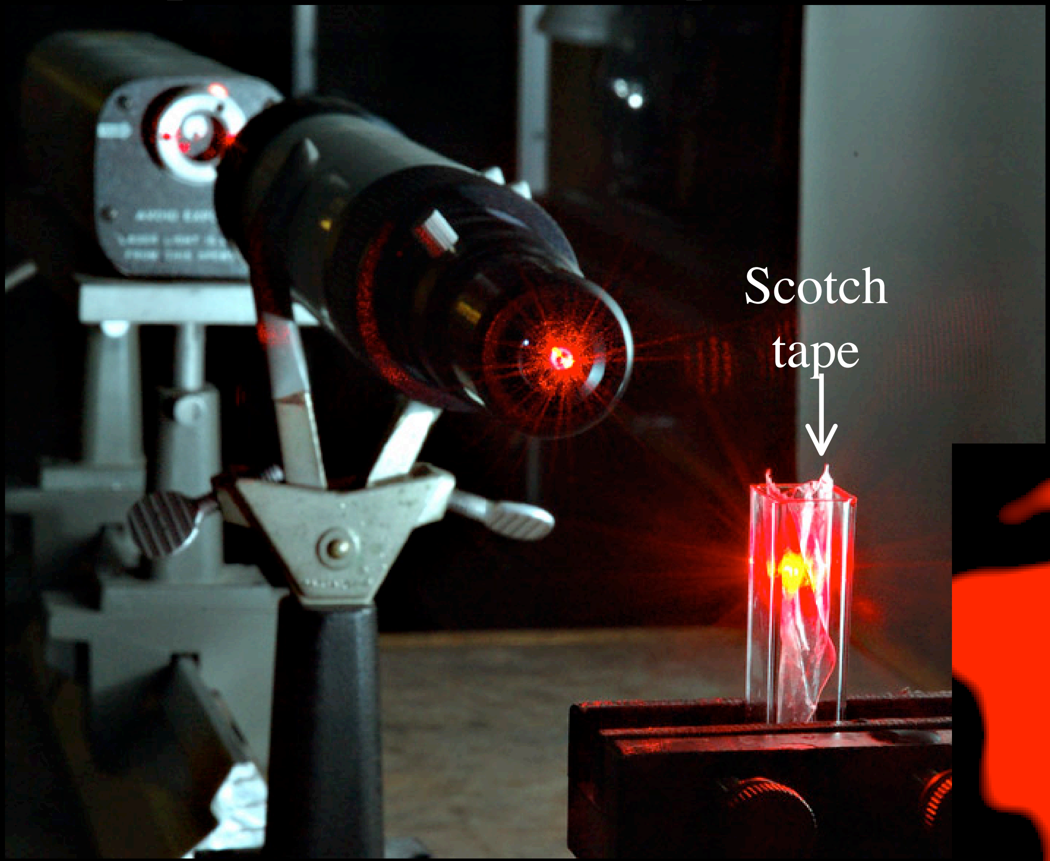
Pulsars are Small

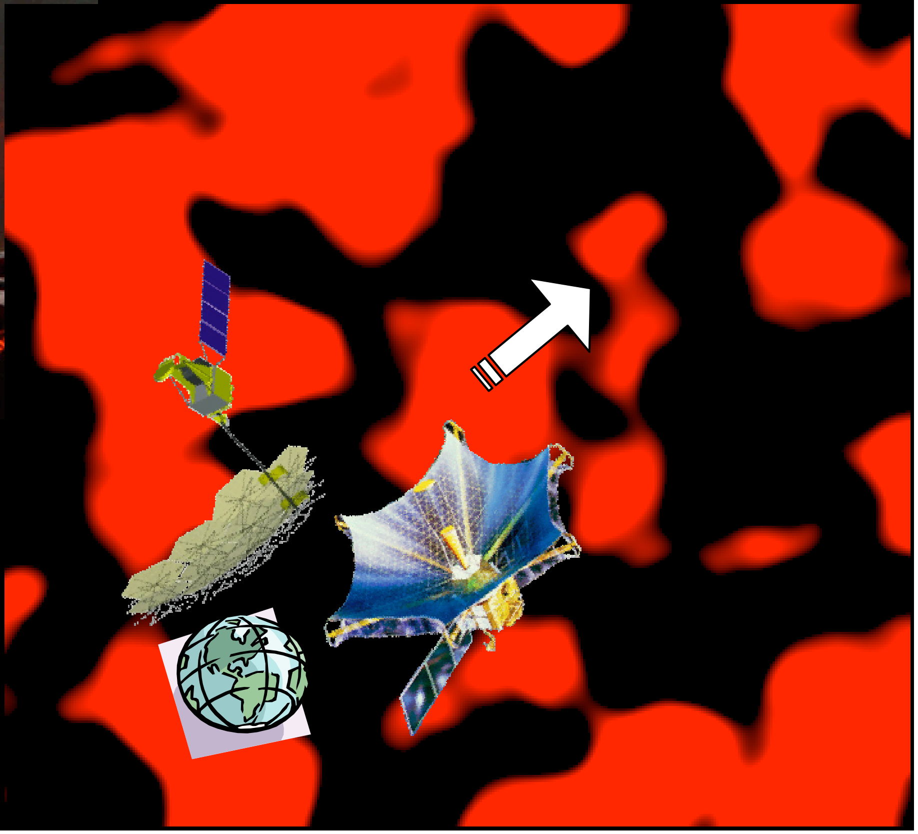


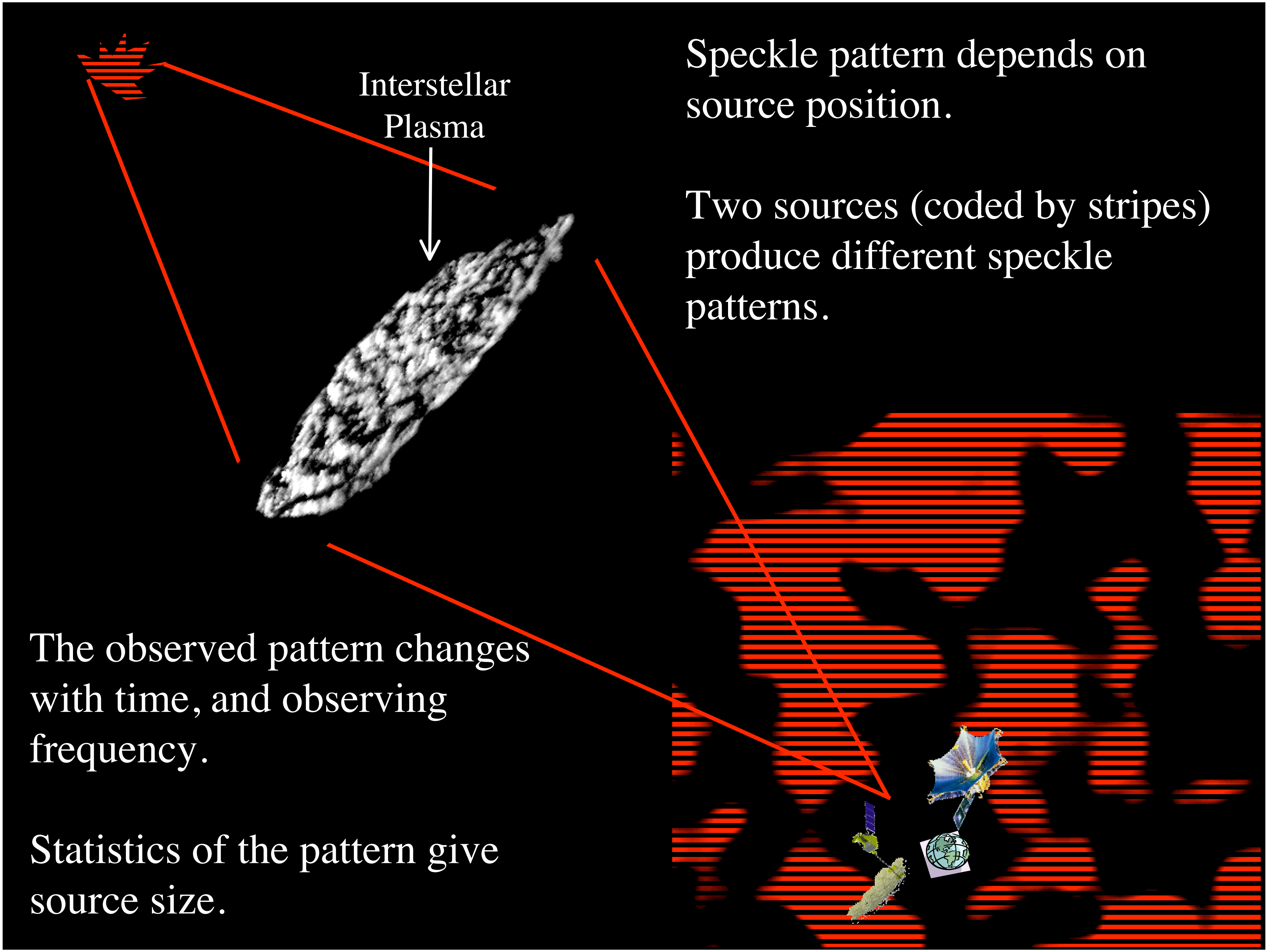
Radio emission region≈300 km

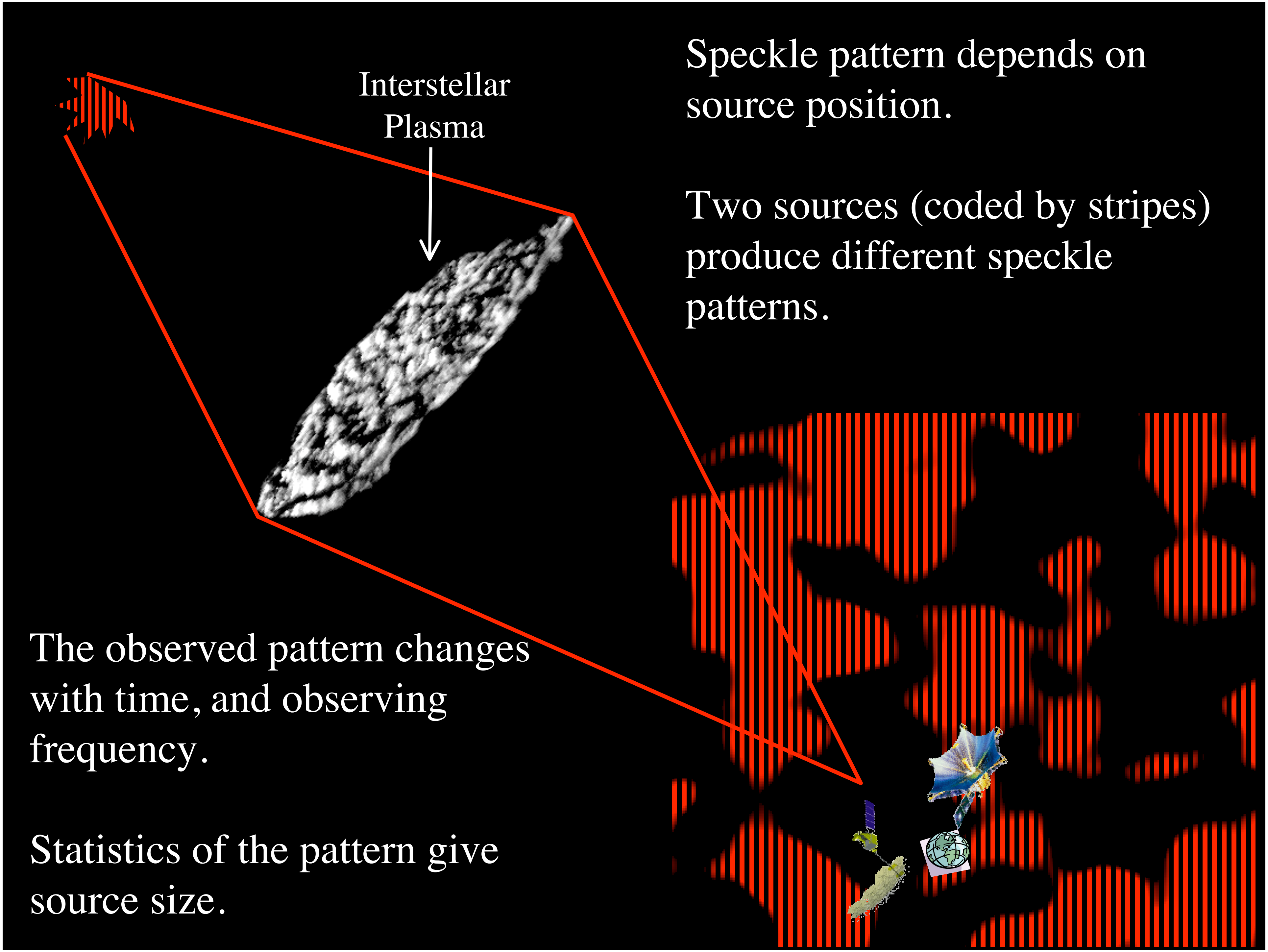
Neutron star≈15 km

Scintillation: Light Traveling Along Different Paths Interferes, and the Speckle Pattern Sweeps Past Earth






Interstellar Plasma
Speckle pattern depends on source position.
Two sources (coded by stripes) produce different speckle patterns.
The observed pattern changes with time, and observing frequency.
Statistics of the pattern give source size.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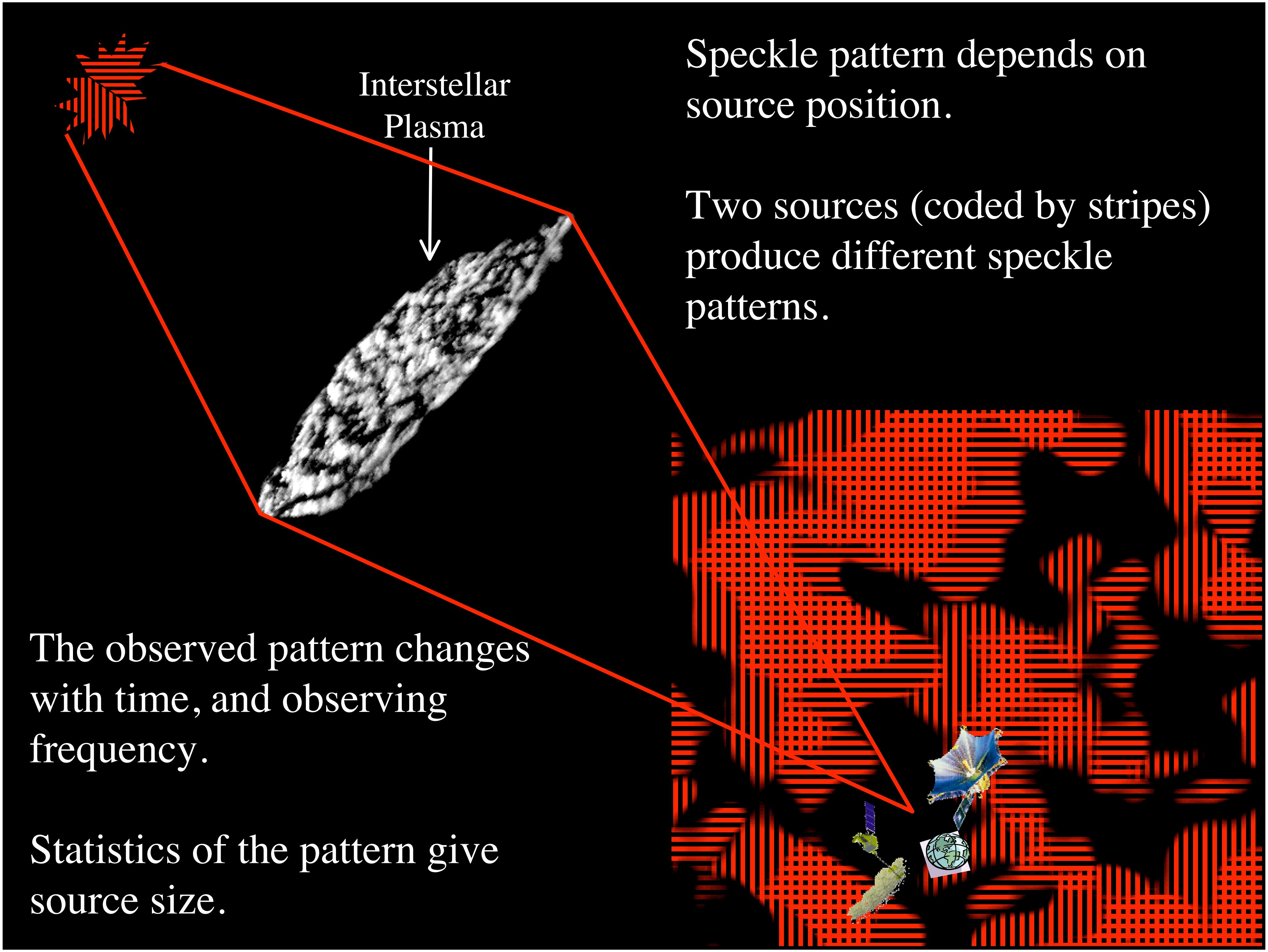
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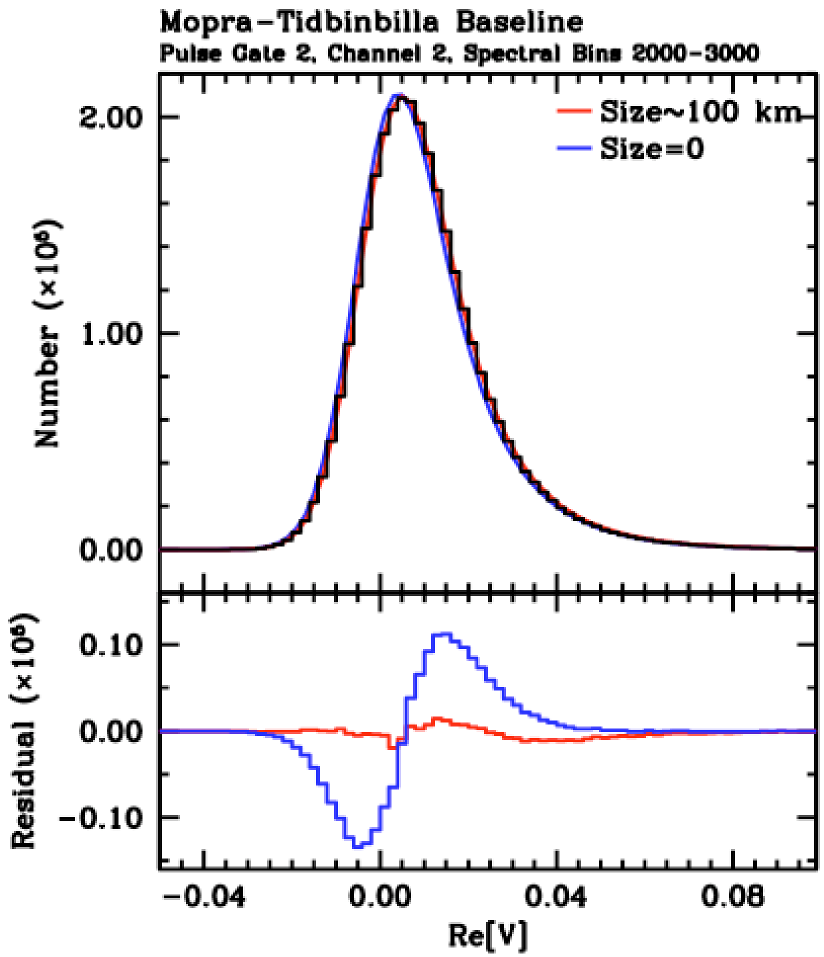
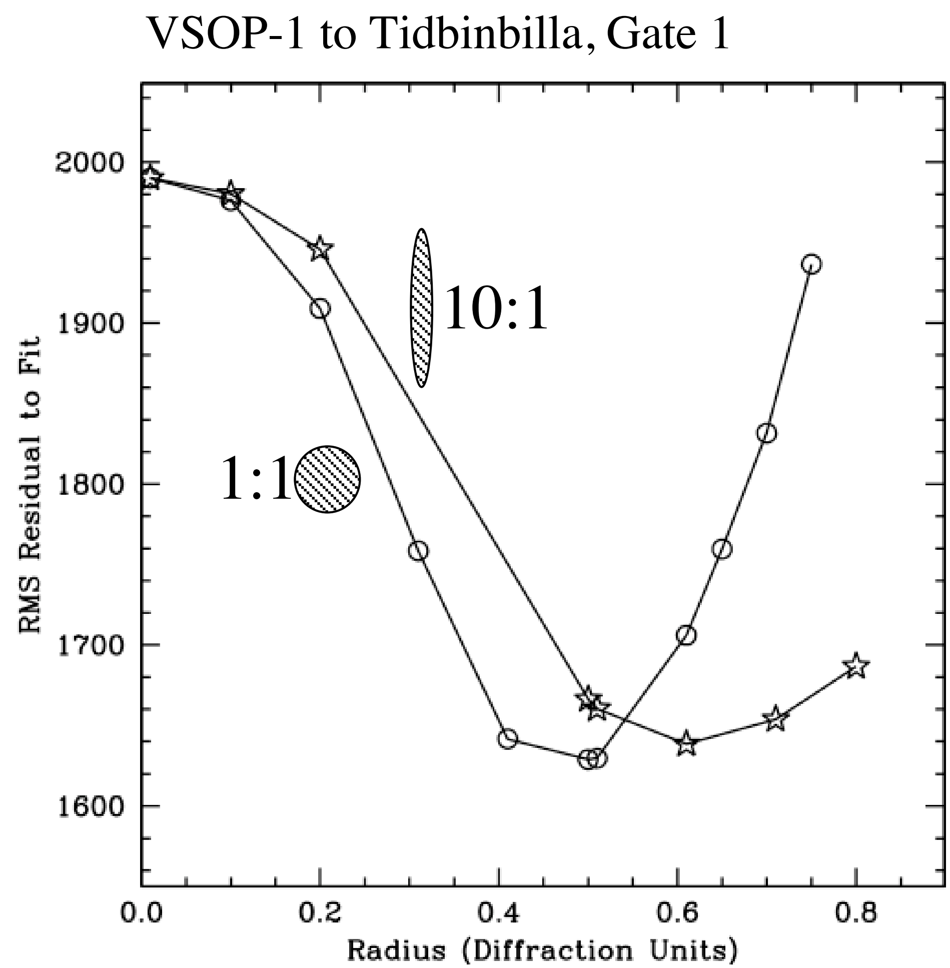
Vela Pulsar

- Size measurement works best for the Vela Pulsar: heavily scattered, strong enough to detect in 1 scintillation time$\times$1 scintillation bandwidth
- 3 Important Things:
  - Distribution of Noise
  - Distribution of Visibility (including source size effects)
  - Speedy Fit of model to observations

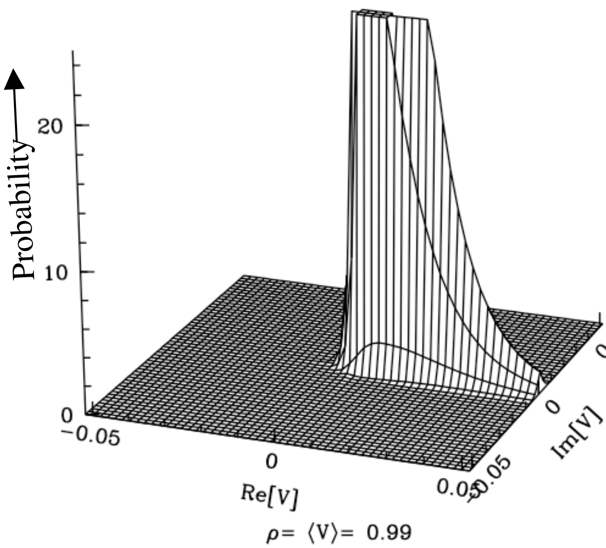
Fit for VSOP-1 data:

- Calculate model visibility distribution (including sou size)
- Add noise: *not* a convolution
- Project to 1D: number N(Re[V]), mean square Im[V]
- Nonlinear fit to data

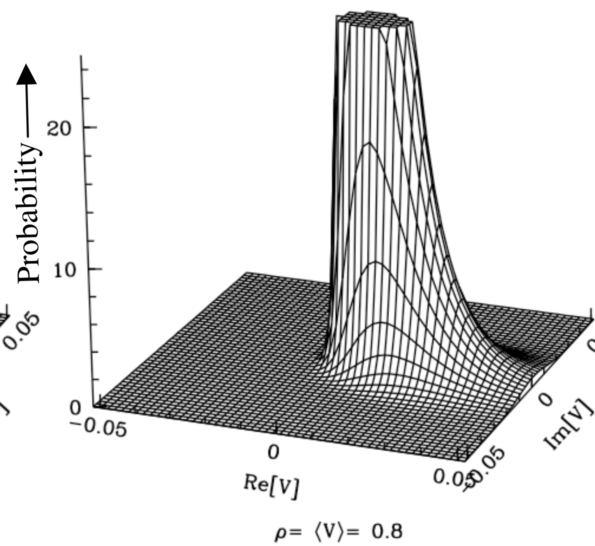




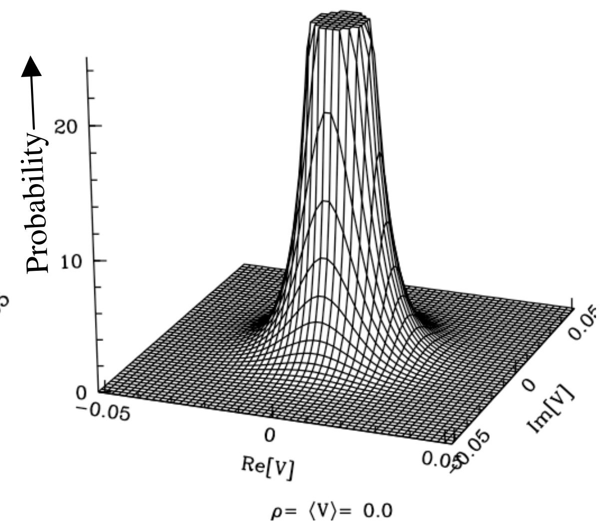
Distribution of Visibility for a Scintillating Point Source



Zero Baseline



Short Baseline



Long Baseline

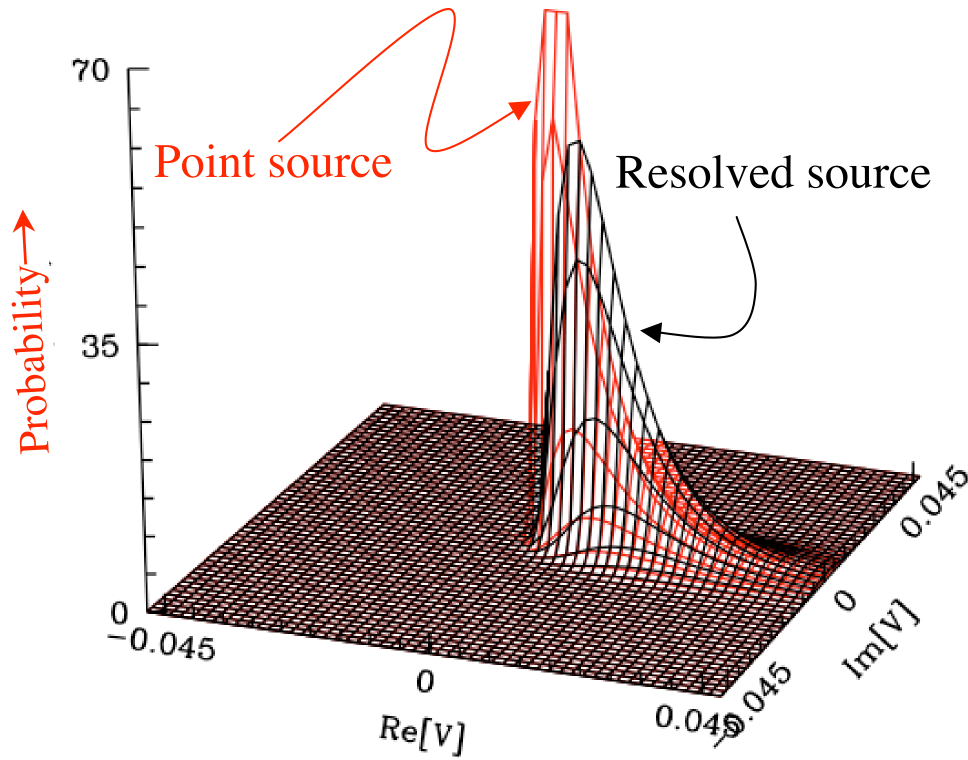
For 0 baseline, the distribution of visibility is exponential along Re[V] (=distribution of intensity for a single dish).

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

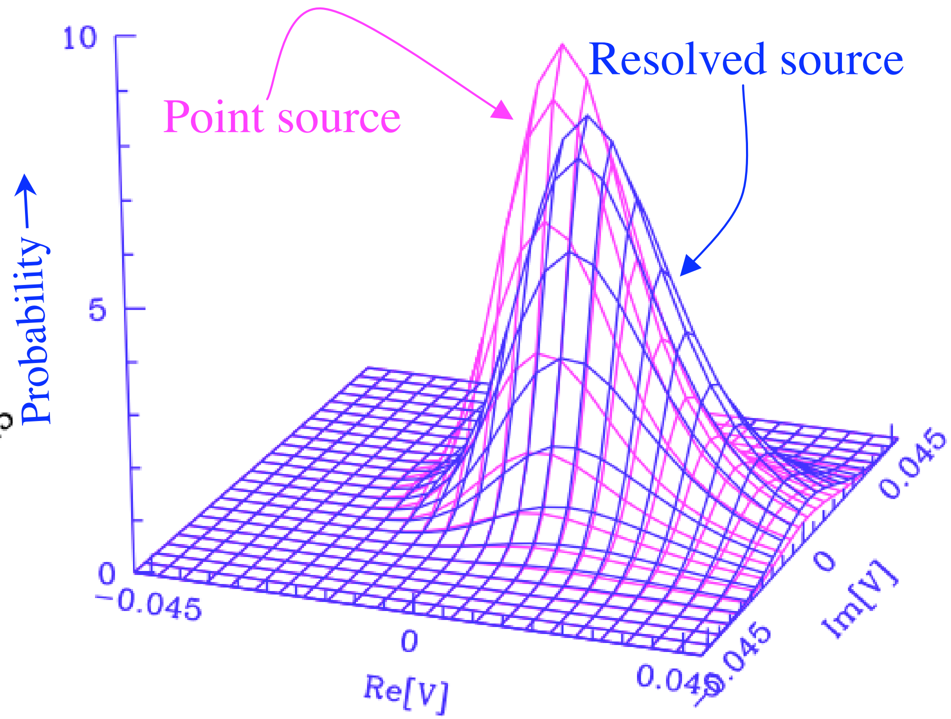
For long baselines, the distribution is circular (phase is random).

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

Effects of Source Structure+Noise



No Noise



With Noise (as Measured)

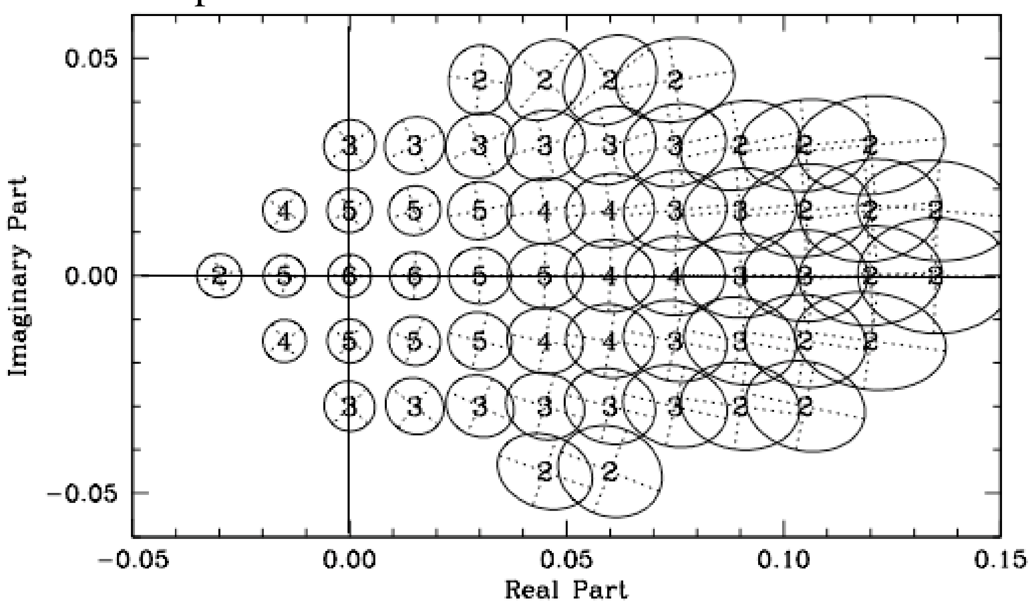
If the source is resolved, the peak is "softer", and shifted toward +Re[V];
the distribution is wider in Im[V].

With added instrumental and source noise, the peak is softer and the distribution is wider, but the centroid remains near 0.

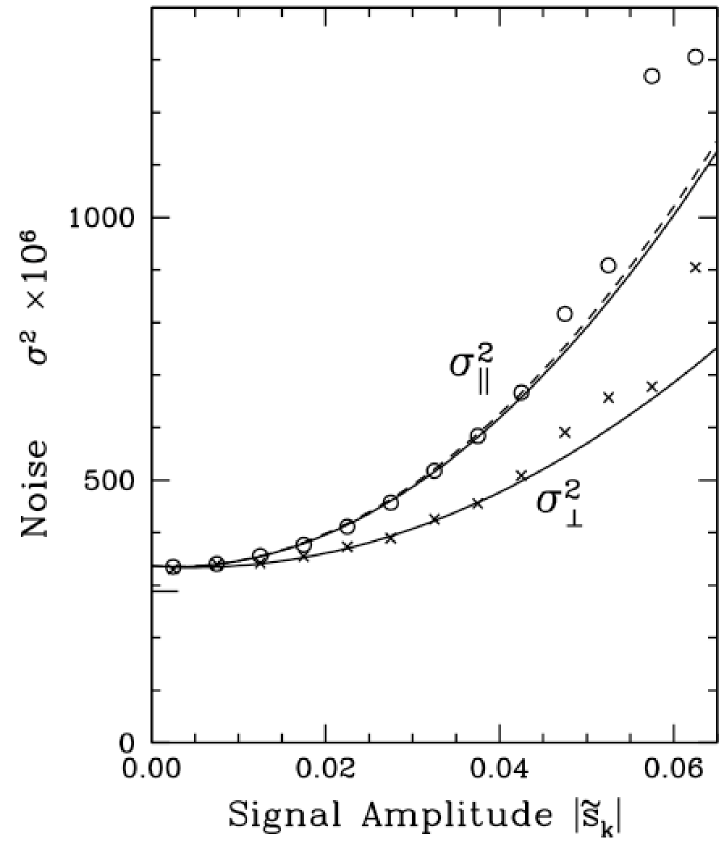
Distribution of Noise

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

Mopra-Tidbinbilla baseline



VSOP-1 - Tidbinbilla baseline



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

Excellent correlator design and performance are critical for stable and understandable noise.

VSOP-2 Observations

- Resolution is *lower* at shorter wavelength
- Scale of scintillation pattern: ~10^4 km
- Scintillation Time x Bandwidth at 8 GHz:
  - 9 MHz x 45 sec
  - Pulsar flux density is ~ 0.13 Jy (no gating)
  - SNR ~ 5 in 1 scintillation element on VSOP-2 to Tidbinbilla Baseline
  - 5x better with pulsar gating

Summary

- Pulsar VLBI is hard
- The results can sometimes be interesting
- VSOP-2 can make some interesting pulsar observations
- This requires:
  - o High-sensitivity observations: big antennas!
    - – Pulsar gate would help
  - o Control of noise at the correlator
  - o Lots of work by investigators