CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

Tripping the Light Fantastic
with an
Intra-Hour Variable Quasar

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IntraDay Variability & violation of the 10^{12}K Inverse Compton limit

2-20 day flickering reported by Heeschen (1984) and followed up with Effelsberg (Heeschen, Krichbaum et al. 1987)

Intrinsic? $T_B > 10^{18}$ K ?

6cm/3cm spectral index - 650nm correlation in 0716+714 (Quirrenbach et al. 1991)

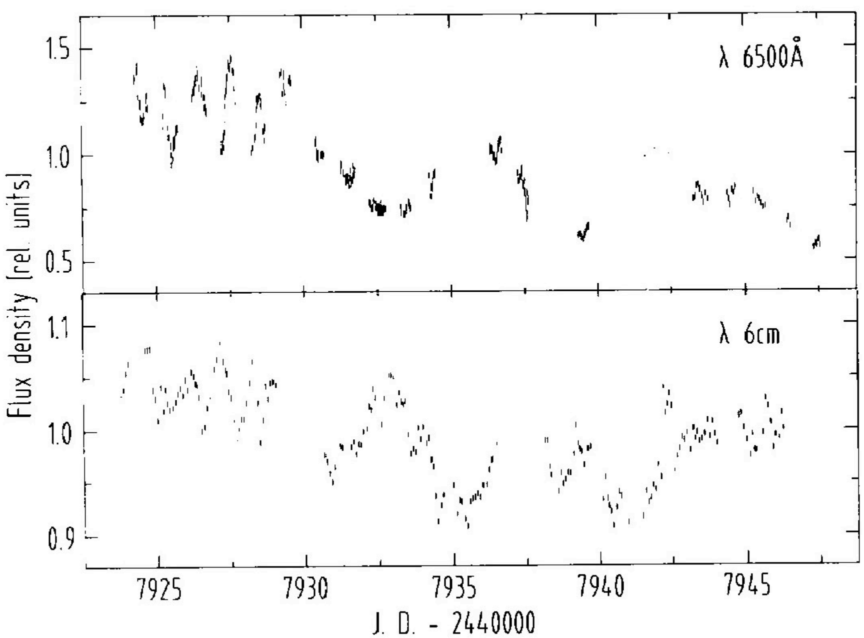
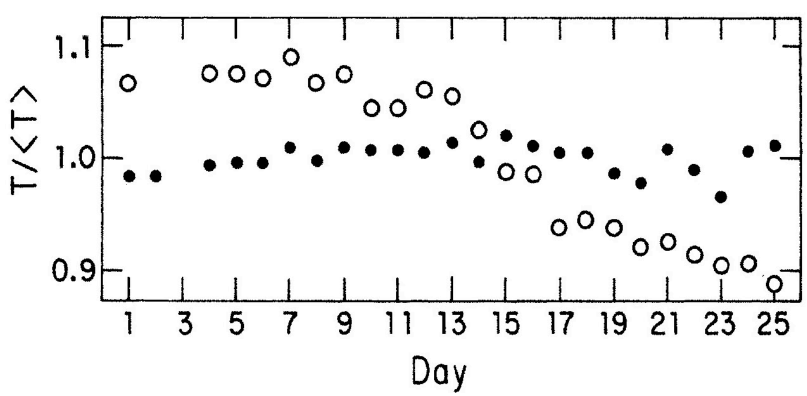


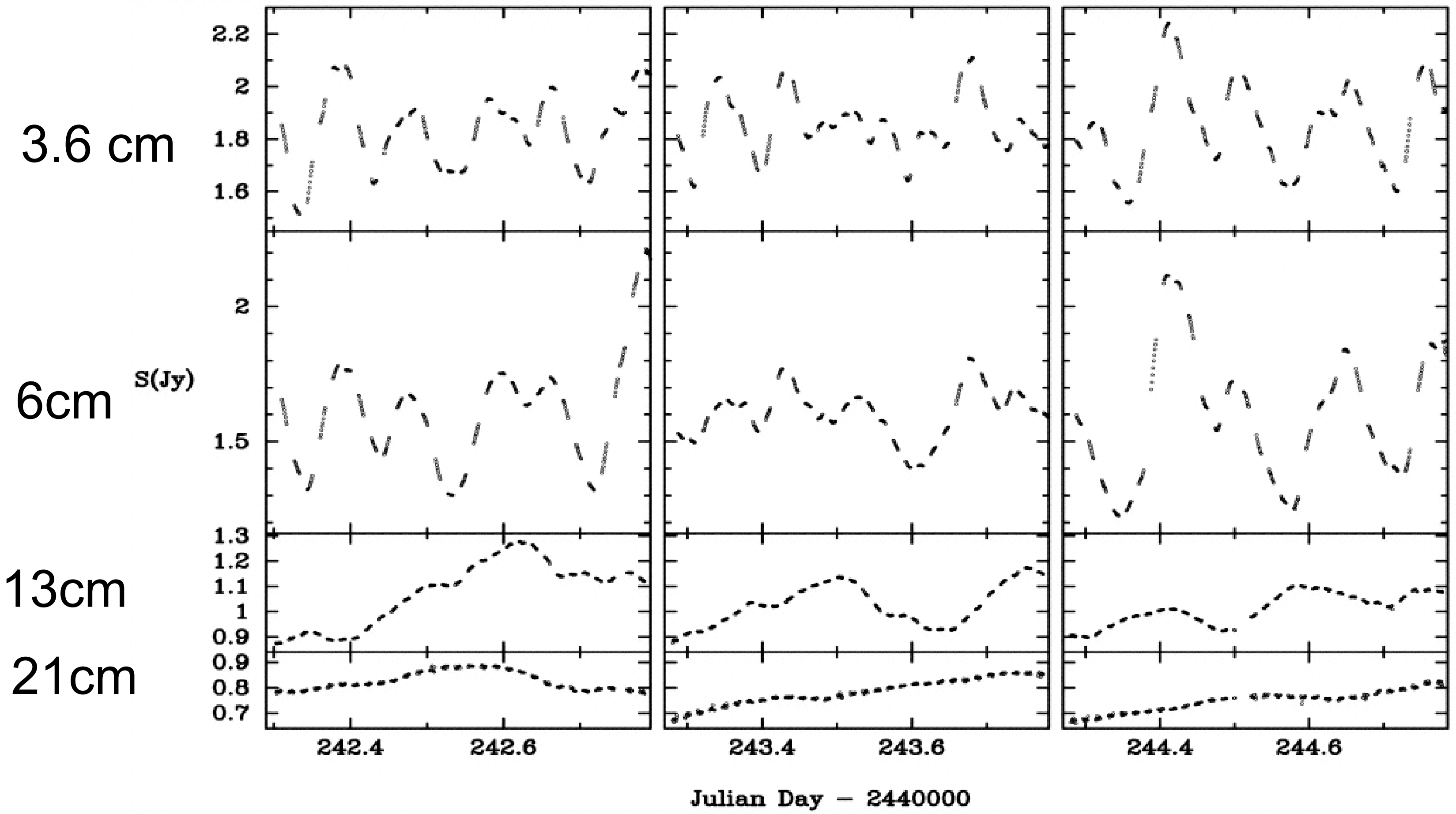
FIG. 1.—Optical (*top*) and radio (*bottom*) light curves of the BL Lacertae

1120 D. S. HEESCHEN: FLICKERING OF EXTRAGALACTIC RADIO SOURCES



Intra-Hour Variability

PKS 0405-385 (Kedziora-Chudczer et al. 1997)



If intrinsic $\theta \sim c\,\Delta t/D \Rightarrow T_{B\mathrm{intrinsic}} \sim 10^{21}$K

If scintillation @1kpc $T_B \sim 10^{15}$K

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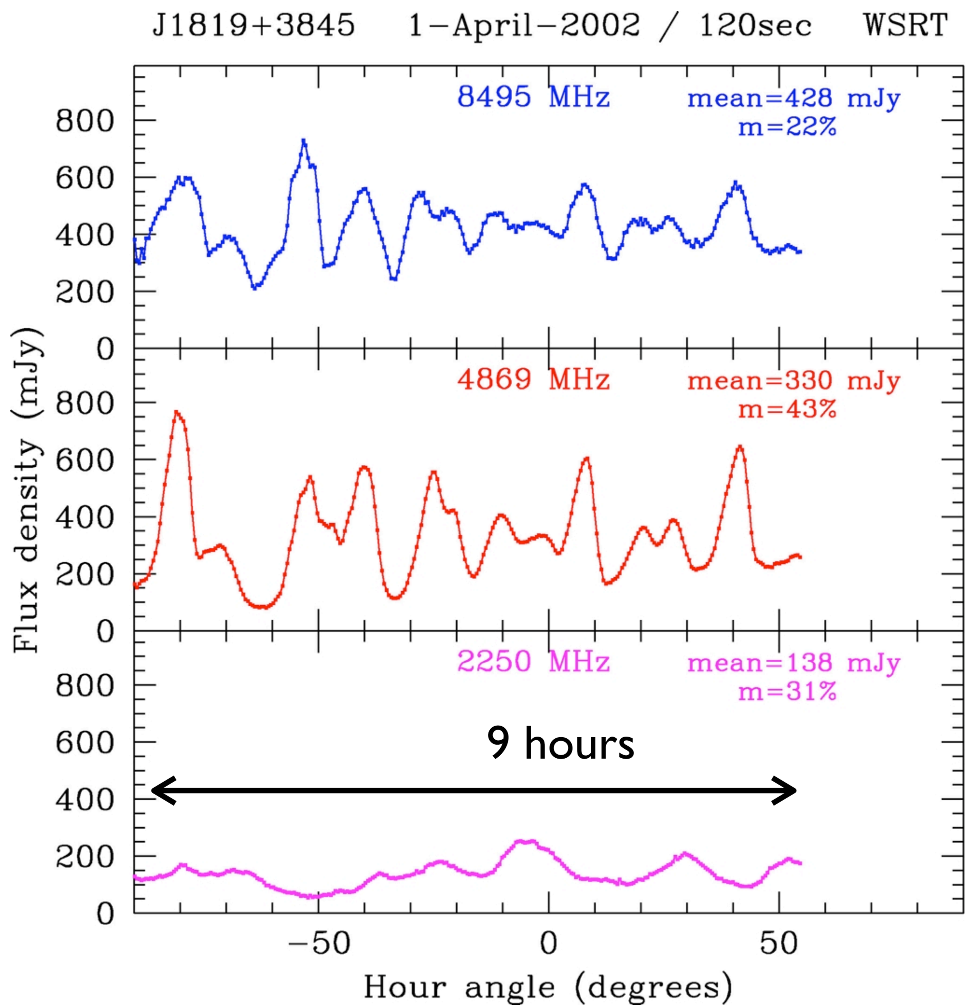
J1819+3845 - The “Scintillator”

discovered by *Dennett-Thorpe & de Bruyn 1999*

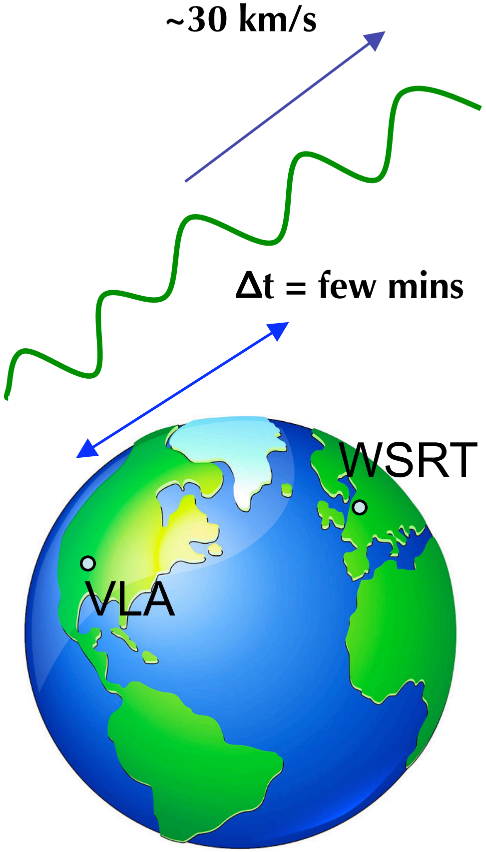
- The fastest, most variable intra-day variable AGN known
- 25-40% modulations at 6cm

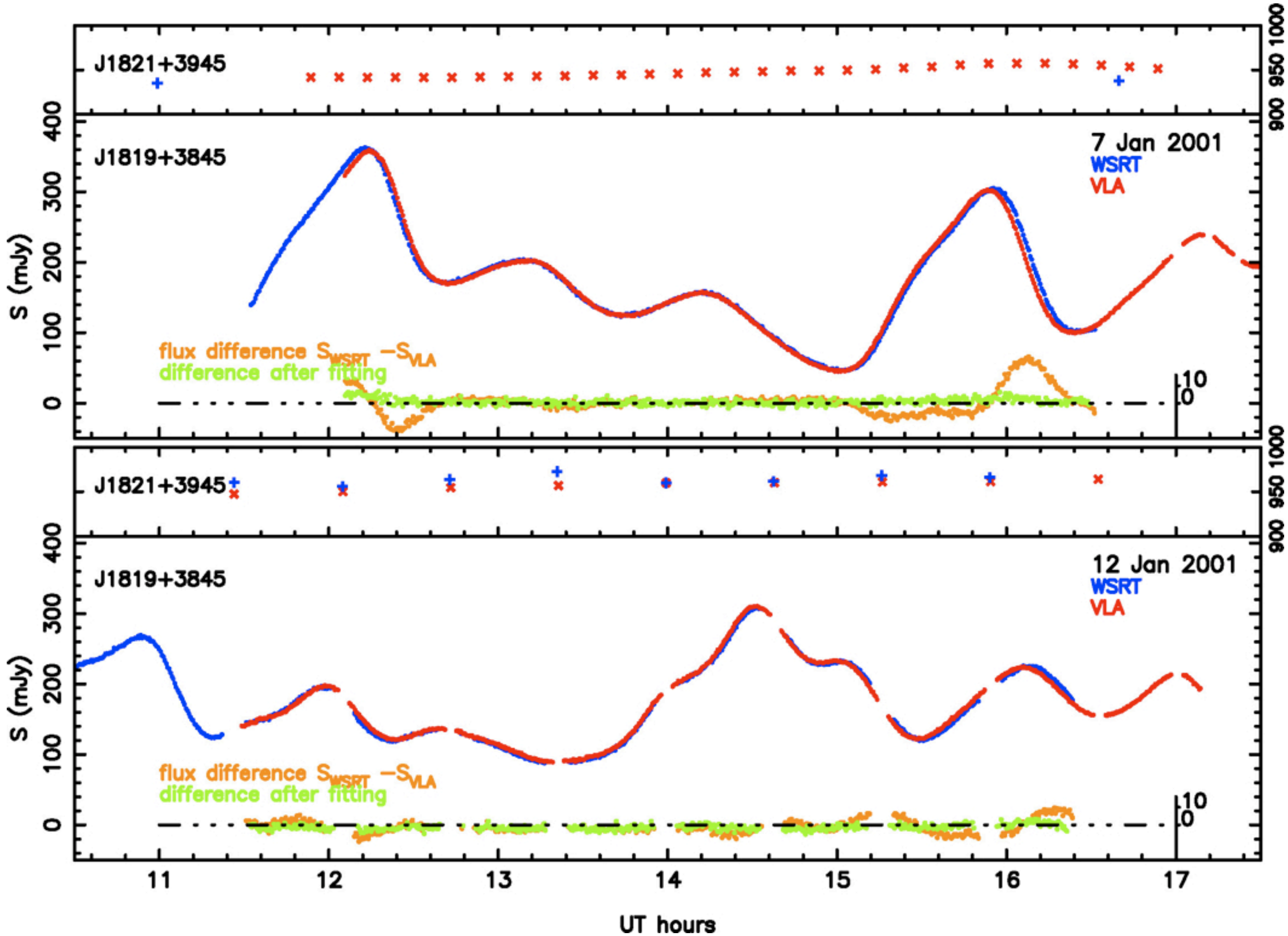


Scintillation-induced variability

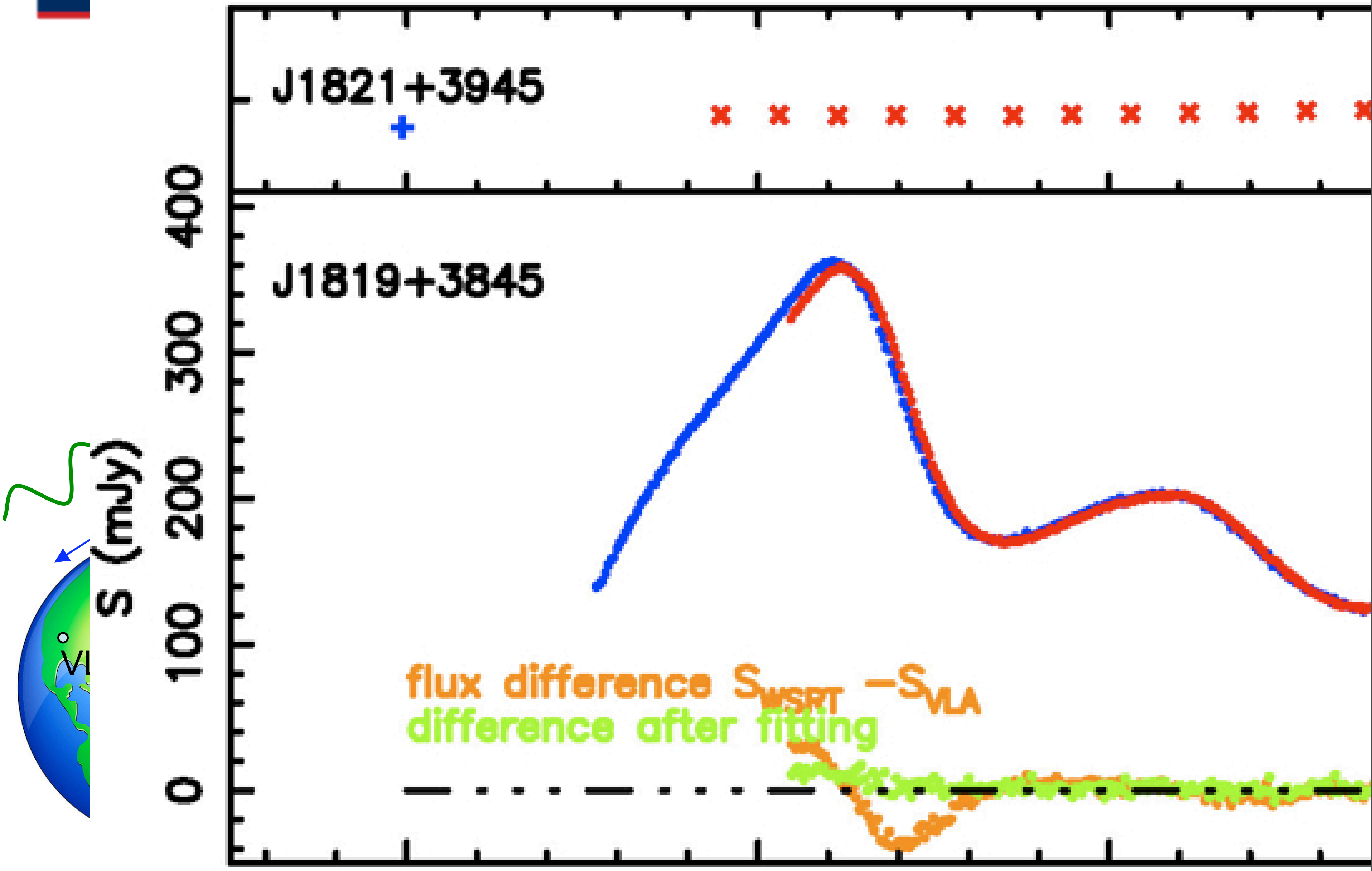
Time delay between telescopes

Dennett-Thorpe & de Bruyn, Nature 2002



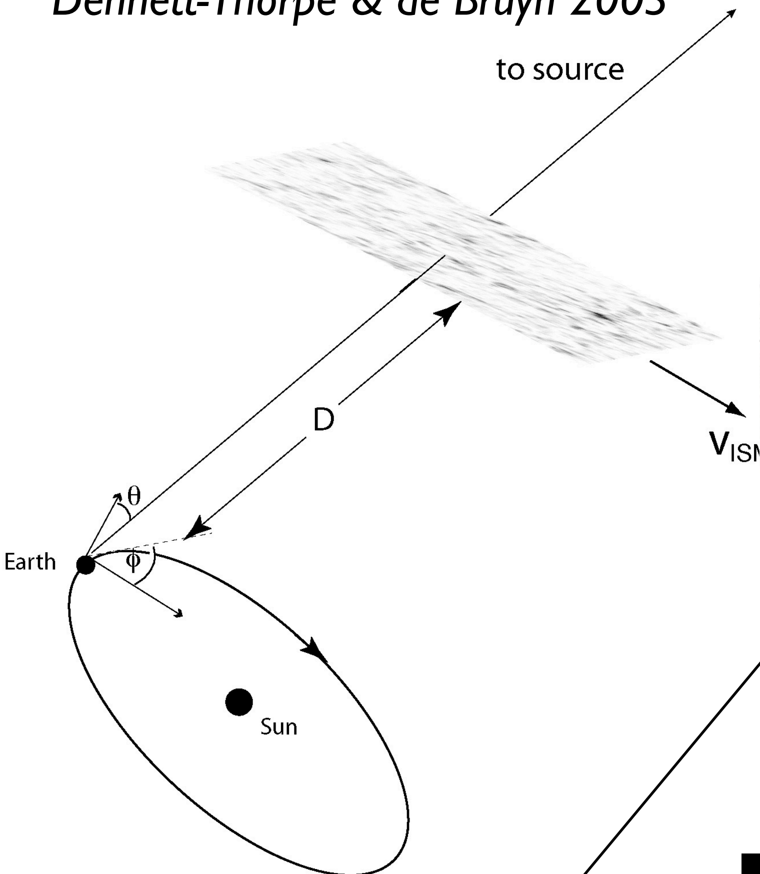


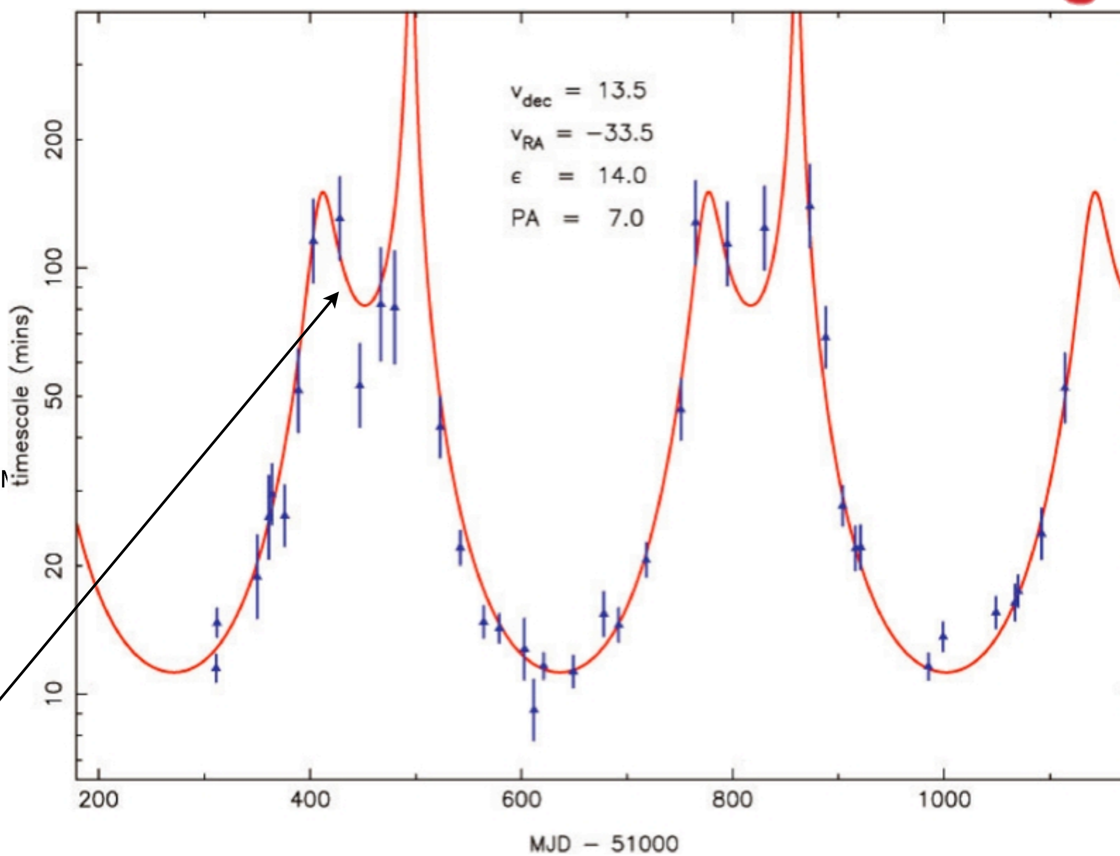
Scintillation-induced variability



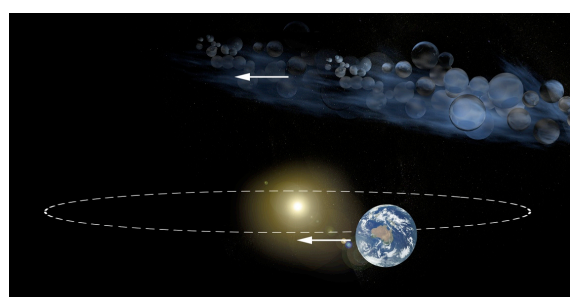
Annual cycle

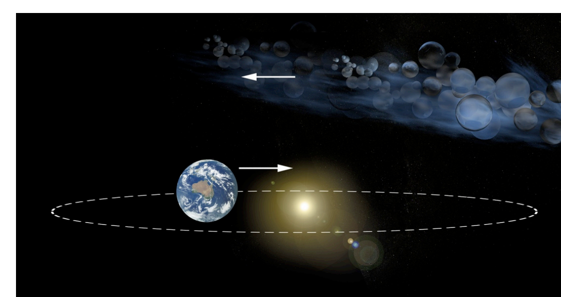
Dennett-Thorpe & de Bruyn 2003





Requires highly elongated (R>14) scintillations!



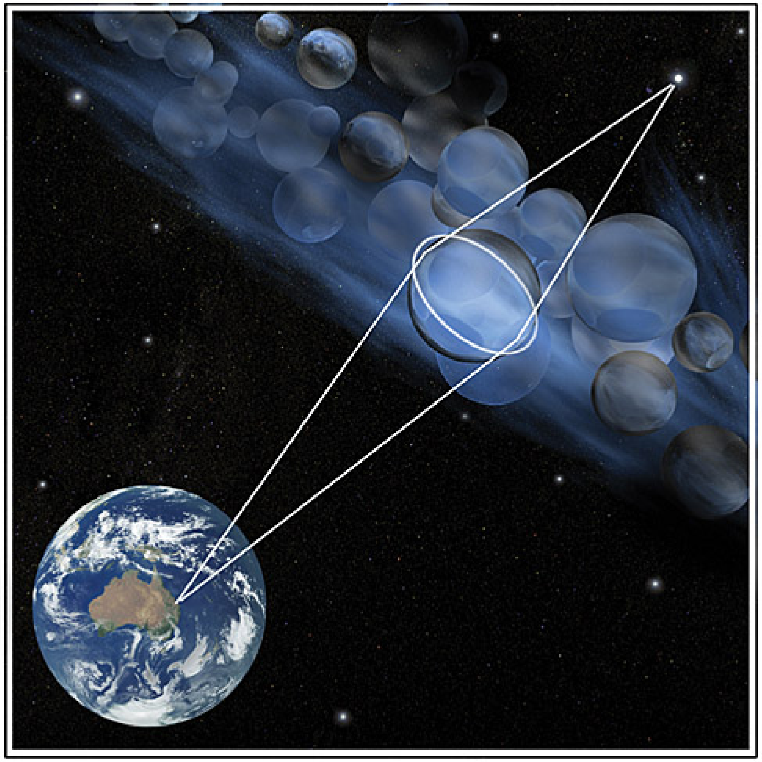


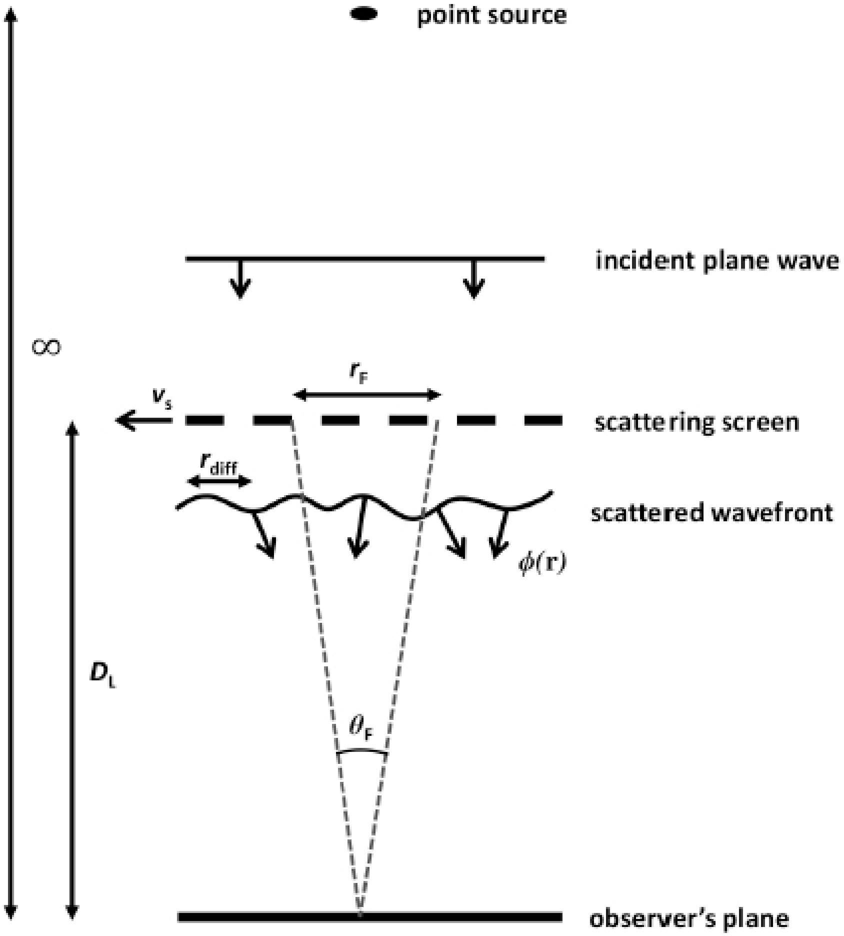
The Size of a Scintillating Source

Scintillation physics implies a size: $\theta_{\mathrm{src}} \sim \theta_{\mathrm{F}} = \sqrt{\frac{\lambda}{2\pi D_{\mathrm{ISM}}}}$

D_{ISM} ~ 1-2000pc, and for D_{ISM}=30 pc at 6 cm this means a size of

20 micro-arcseconds





"This is all very good, but what does it *mean*?"

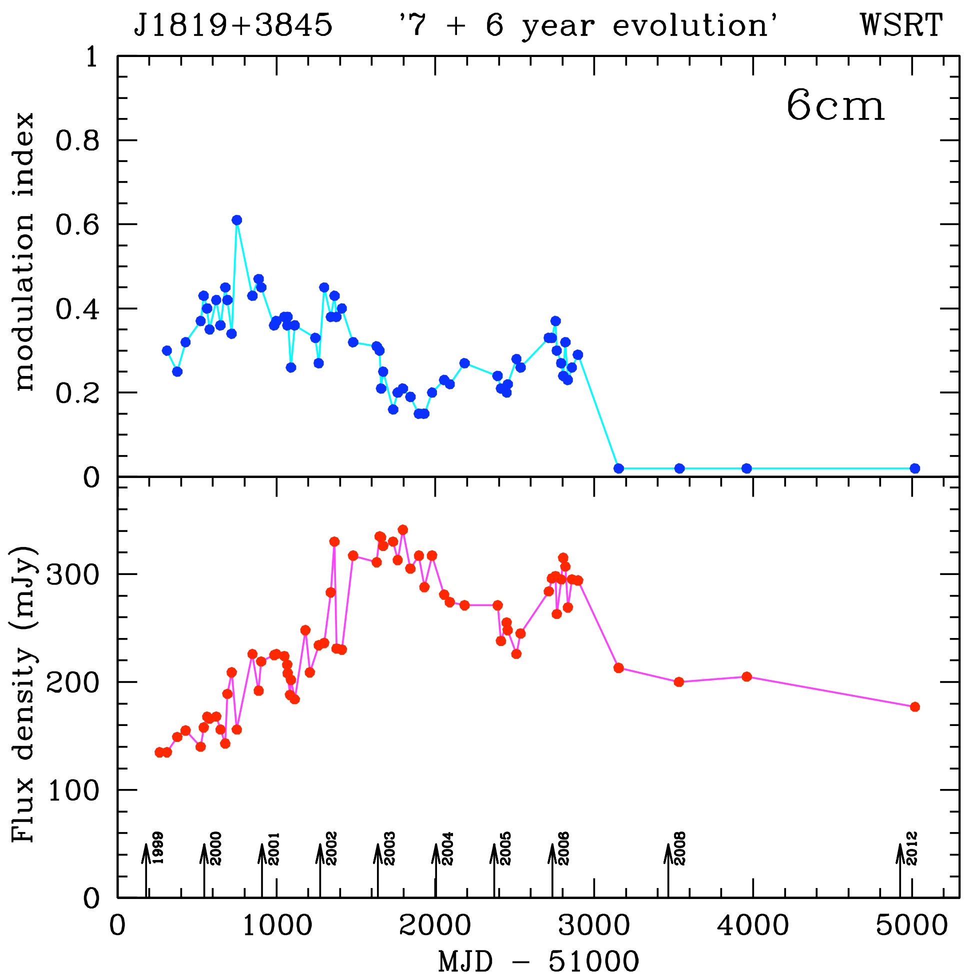
What have we learnt from the scintillations in J1819?

- The scattering is from a cloud less than 1-2 pc from Earth
  - *One of the nearest objects outside the solar system!*
- The turbulence is highly anisotropic
- There is micro-arcsecond structure in *I*, *Q* and *U* and it changes on timescales of years (or less)
- J1819 has stopped scintillating: screen properties

details in de Bruyn & Macquart, A&A submitted

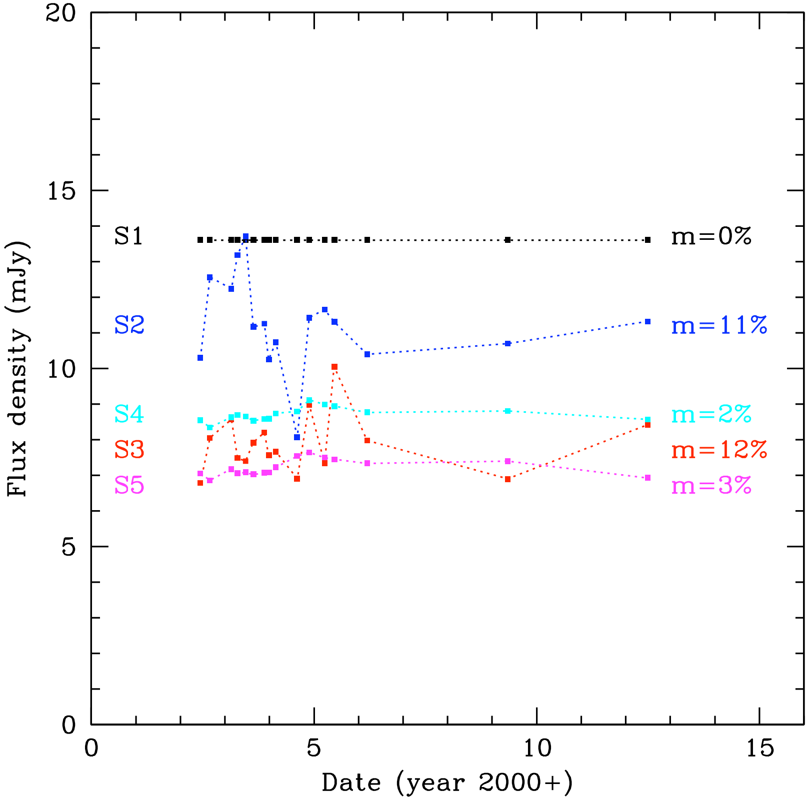
RIP J1819

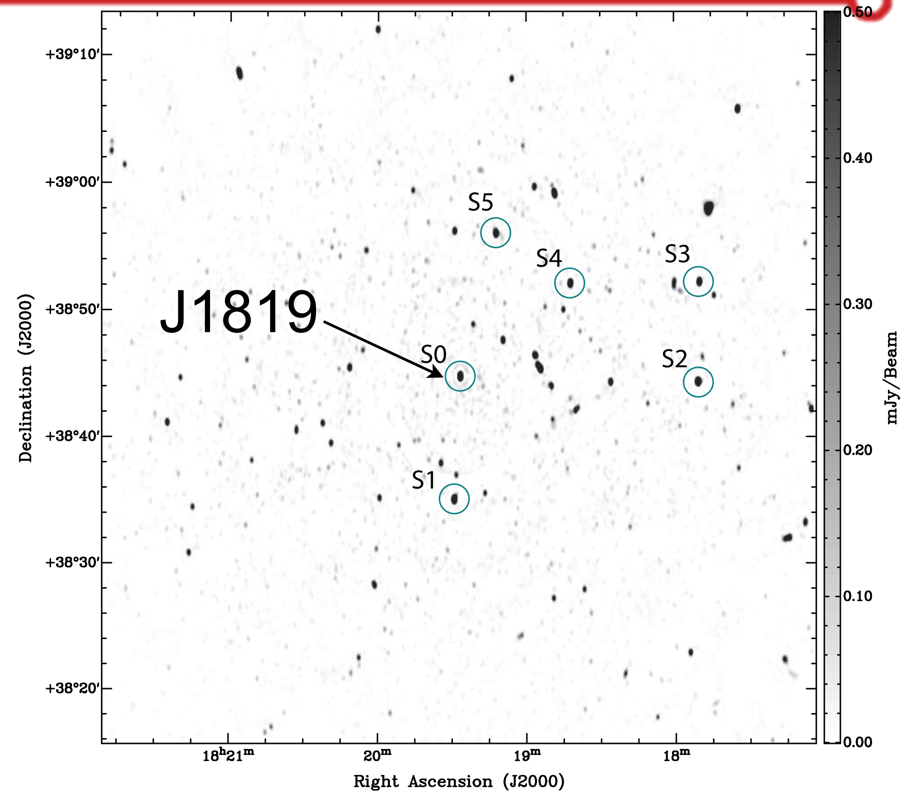
- Modulations now <1%
- Scintillations ceased because the screen moved past the line of sight
- ...not because the source expanded
  - decrease in modulations require source >360 μas
  - VLBA observations post-cessation place a 3σ upper limit of 350 μas
  - Abruptness of cessation (<7mths) means screen edge is <5 AU



RIP J1819

- Duration of scintillations 1999-2007 implies a transverse cloud extent of >59 AU (>1″ at 1pc)
  - Indications that J1819 was variable in 1986-7 Greenbank survey data

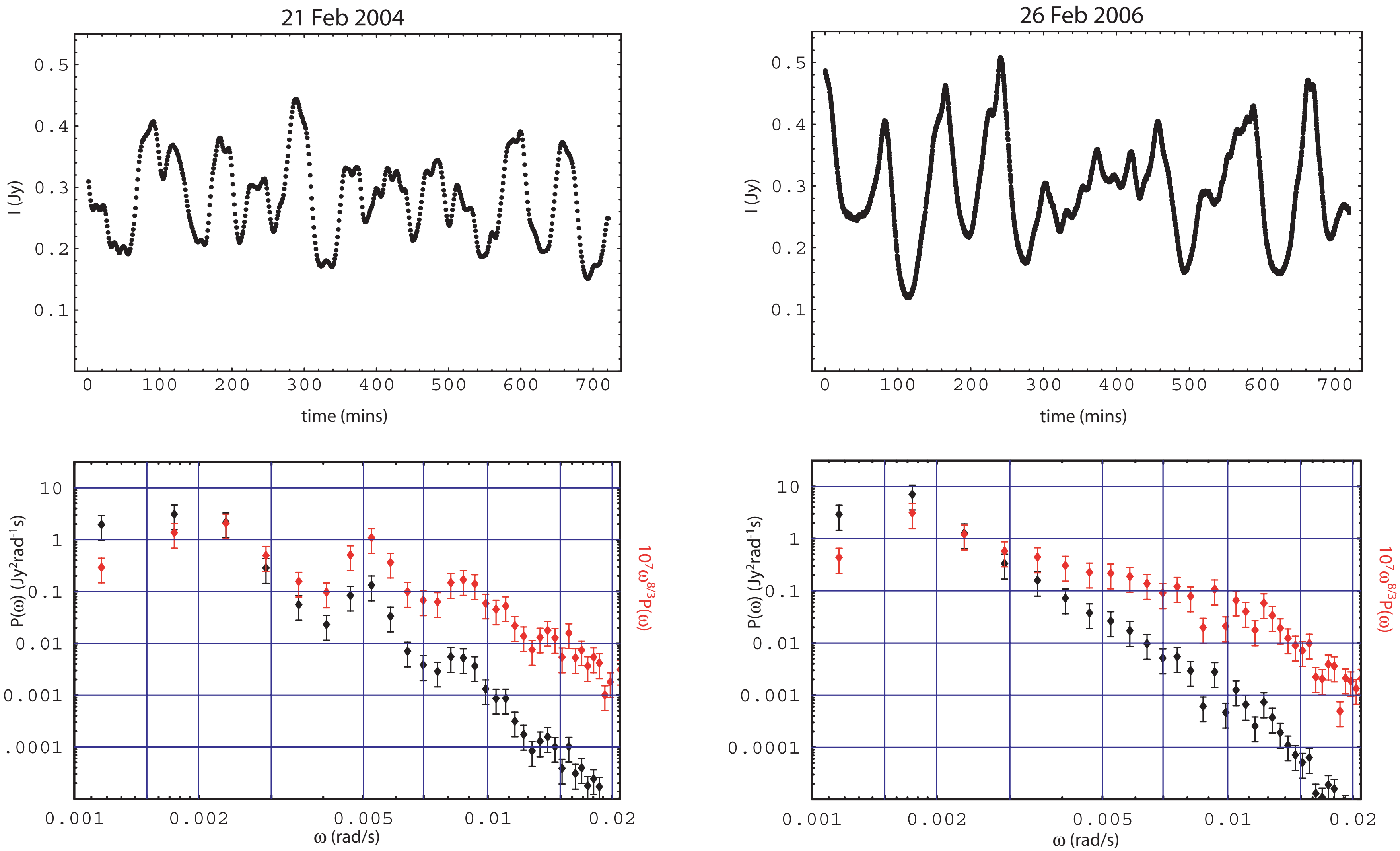




- Search of nearby steep/flat-spectrum sources revealed no significant ISS
- Screen is either patchy or <10′

Structure & ISM Modelling

Macquart & de Bruyn, MNRAS 2007



Structure & ISM Modelling

$$P(\mathbf{q}) \quad = \quad P_{\rm scint}(\mathbf{q}) \left| V\left(\frac{D_{\rm ISM}\mathbf{q}}{k}\right)\right|^2,$$

$$P_{\rm scint}(\mathbf{q}) \quad = \quad 8\pi r_e^2 \lambda^2 \Phi_{N_e}(\mathbf{q}) \sin^2\left(\frac{q^2 D_{\rm ISM}}{2k}\right)$$

Isotropic turbulence:

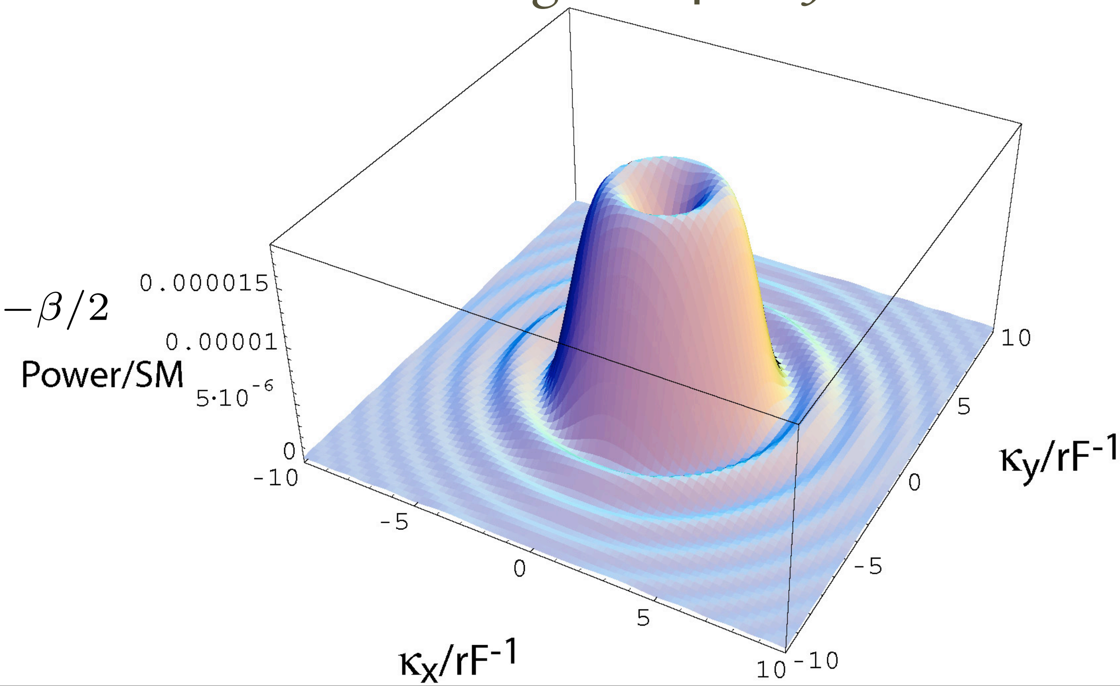
$$\Phi_{N_e}(\mathbf{q}) \quad = \quad {\rm SM}\, q^{-\beta}$$

Anisotropic turbulence:

$$\Phi_{N_e}(\mathbf{q}) \quad = \quad {\rm SM}\left(\frac{q_x^2}{R} + R q_y^2\right)^{-\beta/2}$$

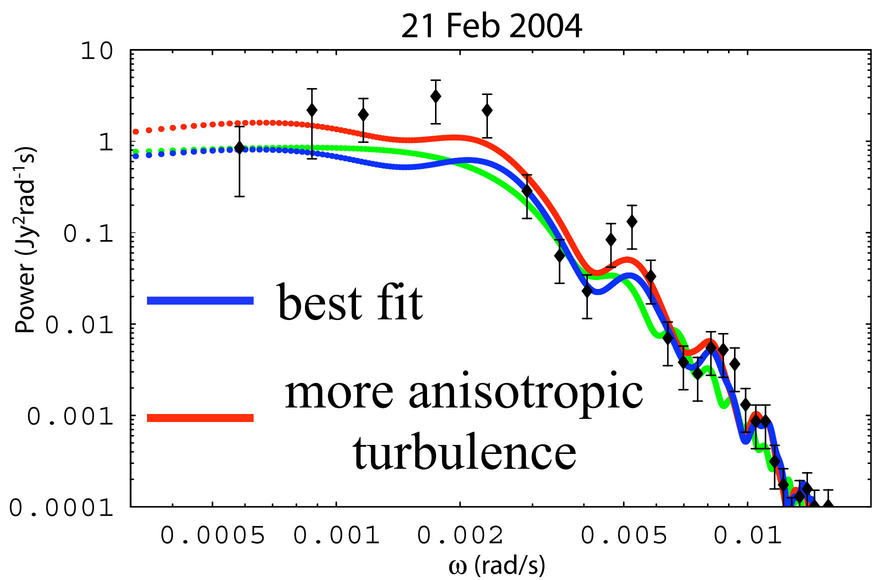
$$\boxed{{\rm SM} \quad = \quad C_N^2 \Delta L}$$

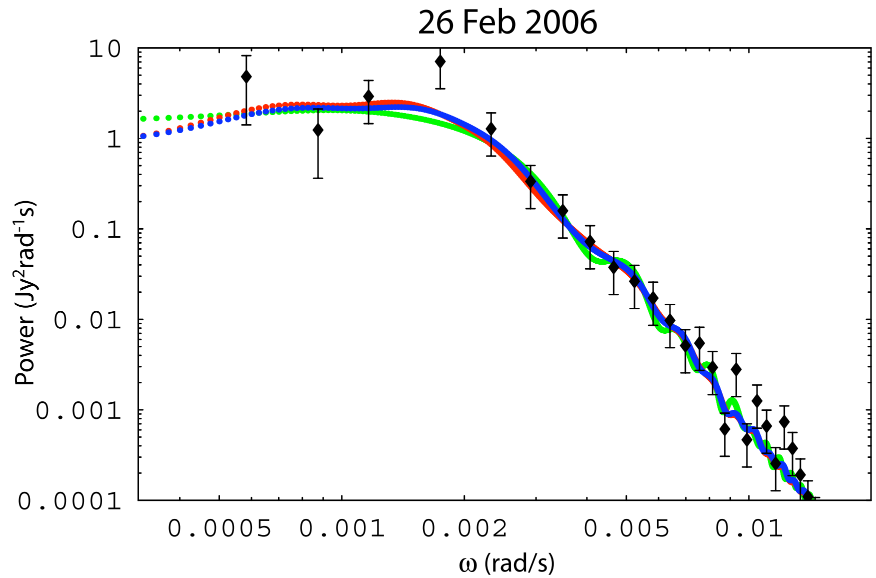
$P_{\rm scint}(\mathbf{q})$ for Kolmogorov (β=11/3) turbulence



Structure Modelling

- Fit the 2004 (fast oscillations) and 2006 (normal variations) data simultaneously to ensure identical turbulence parameters.
- Model structure: two sources with separation $\Delta\theta$, orientation α, sizes θ_1, θ_2 and flux densities I_1, I_2
- Model ISM: screen distance (z), SM, anisotropy (R), v_{ISS}, anisotropy angle





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Screen Distance

	Fit Parameter		
	SM ($10^{17}\mathrm{m}^{-5.67}$)		2.6 ± 0.2
screen distance	z (pc)		3.8 ± 0.3
	v_{ISS} ($\mathrm{km\,s^{-1}}$)		59.0 ± 0.5
mildly anisotropic turbulence	R		2.9 ± 1.0
	θ (rad)		2.26 ± 0.02
		2004	2006
	I_1 (mJy)	42 ± 7	67 ± 11
	I_2 (mJy)	11 ± 4	17 ± 12
component separation (change implies apparent expansion speed of 3.4c)	$\Delta\theta$ (μas)	240 ± 15	565 ± 15
	α (rad)	0.00 ± 0.03	2.4 ± 0.3
small angular sizes required (but not all well determined)	θ_1 (μas)	16 ± 1	20 ± 3
	θ_2 (μas)	16 ± 2	7 ± 4

A highly turbulent screen

- Peak $T_B = 1 \times 10^{13}$ K
- Exceptionally strong turbulence only 4 pc from Earth, thickness ≲0.4pc.
  - $C_N^2 > 17\ \mathrm{m}^{-20/3}$
  - If screen depth comparable to transverse extent

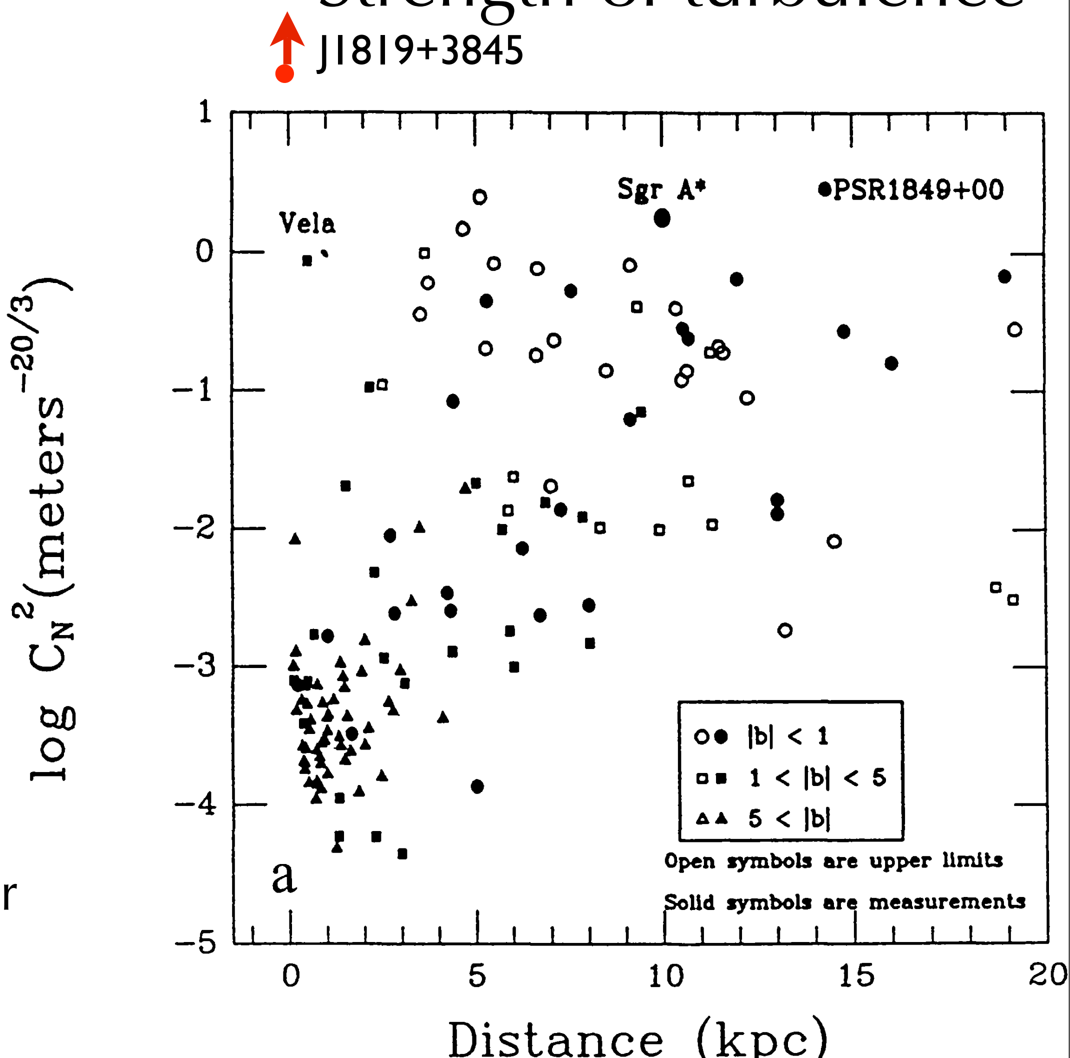
$$\langle n_e \rangle = 97\, l_0^{1/3} \epsilon^{-1} \left(\frac{\Delta L}{100\ \mathrm{AU}} \right)^{-1/2} \quad \mathrm{cm}^{-3}$$

turbulence outer scale

rms of n_e fluctuations relative to mean

  - Similar to densities inferred for ESE clouds: how is J1819's screen related?

Strength of turbulence



Cordes, Spangler, Weisberg & Clifton 1988

A highly turbulent screen

- This implies DM and RM increments of

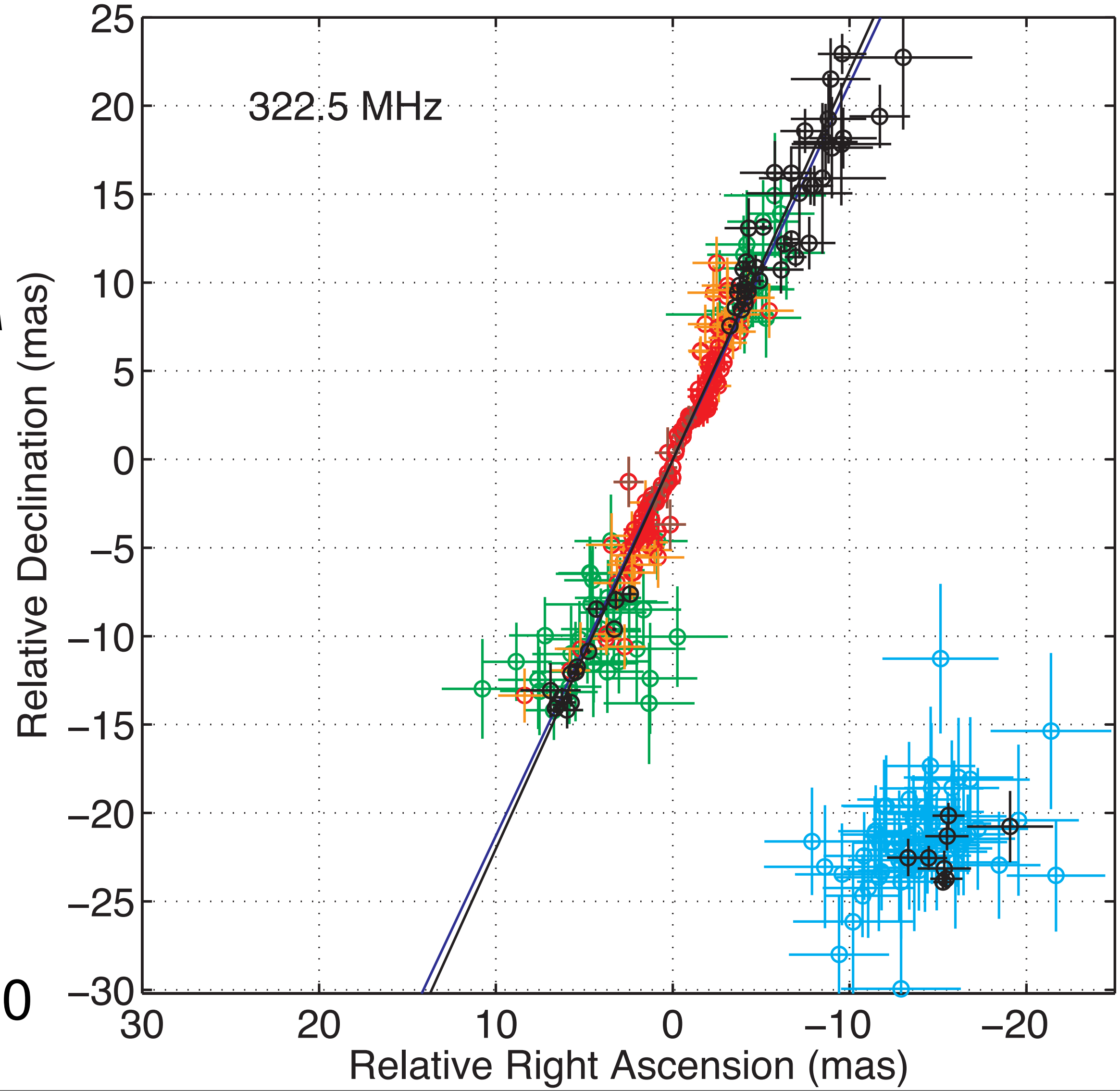
$$\mathrm{DM} = 4.7\, l_0^{1/3} \epsilon^{-1} \left(\frac{\Delta L}{100\ \mathrm{AU}} \right)^{1/2} \ \mathrm{pc\, cm^{-3}}. \qquad \mathrm{RM} = 2.2\, l_0^{1/2}\, T_4^{1/2} \epsilon^{-3/2} \left(\frac{\Delta L}{100\ \mathrm{AU}} \right)^{1/4} \ \mathrm{rad\, m^{-2}}$$

Temp. in units of 10^4K - Magnetic pressure balance assumed

- We are searching for evidence of the RM increment with LOFAR
- Existing WSRT data is inconclusive: the polarization angle of the diffuse emission is smoothly distributed near J1819.
- RM synthesis with scintillating Q, U poses an interesting challenge

Anisotropic Turbulence

J1819's scintles are highly (R>14) anisotropic. Connection to other highly turbulent ISM regions?

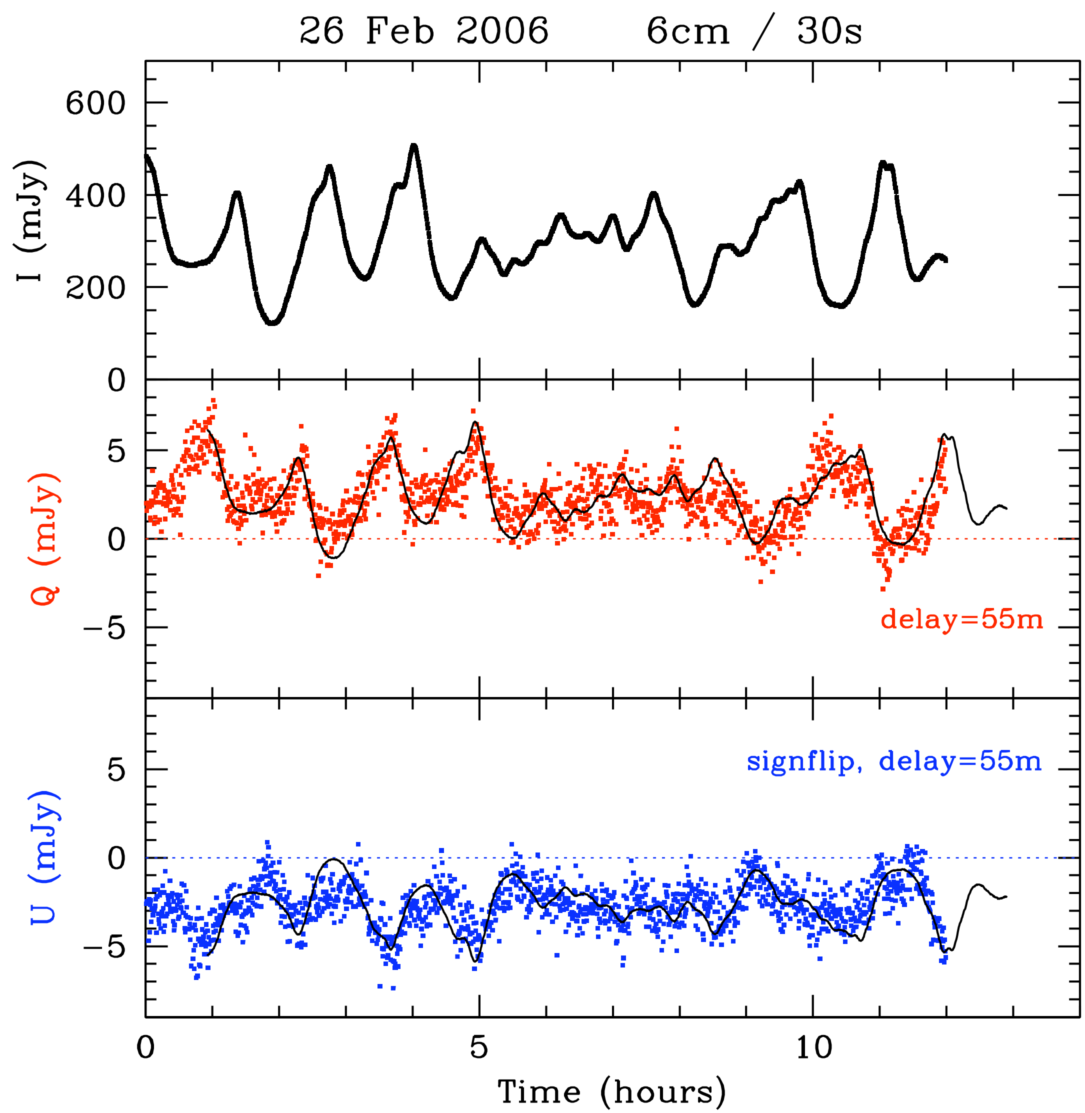


Speckle image of the diffractive scintillations in PSR B0834+06, showing R>30 anisotropy in the turbulence

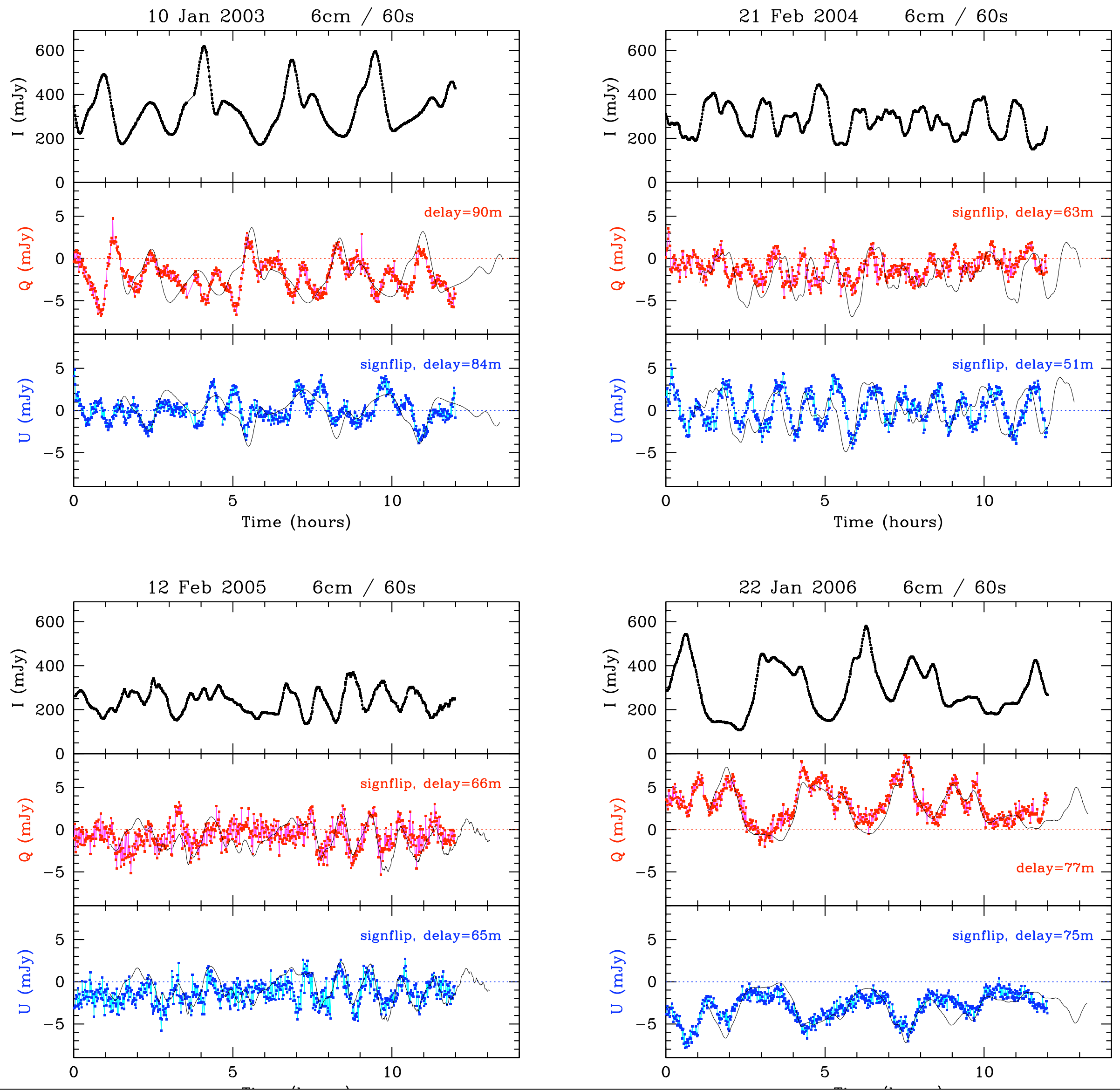
Brisken et al. 2010

Polarization Modelling

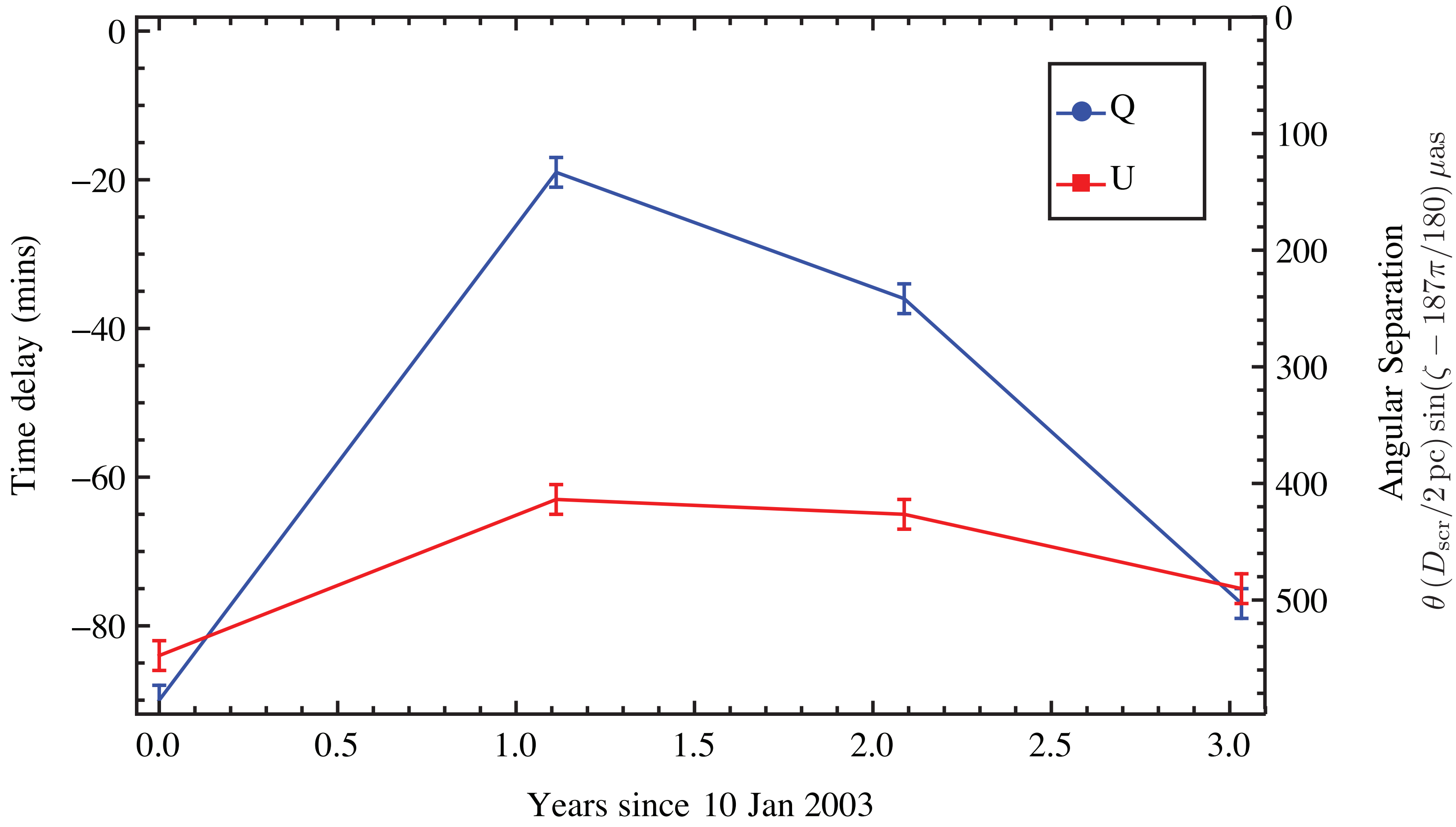
- *Q*, *U* are much more highly modulated than *I*
- Both show significant time delays relative to *I*
- Nature of variations change between epochs
- Comparison of I-Q/U time delay with VLBI image fixes the screen distance at 1.5 ±0.5pc
- We can measure an expansion speed between epochs…



Polarization Modelling



Polarization Modelling



Average component separation 13 μas y^{-1}. 1μas ⇔0.0064pc

So expansion limited to ~0.3c

Aside: IGM scattering limits

- The presence of ISS at the z=0.54 redshift of J1819 limits IGM scattering to

$$\mathrm{SM}_{\mathrm{eff}} < 9.8 \times 10^{16}\,\mathrm{m}^{-17/3}$$

- The absence of temporal smearing in several of the FRBs detected by Thornton et al. (2013) limits the IGM scattering measure at comparable z to

$$\mathrm{SM}_{\mathrm{eff}} < (1+z_L)\left(\frac{\tau}{1\,\mathrm{ms}}\right)\left(\frac{D_{\mathrm{eff}}}{1\,\mathrm{Gpc}}\right)^{-1}\begin{cases} 8.6\times 10^{15}\left(\frac{l_0}{1\,\mathrm{AU}}\right)^{-1/3}\,\mathrm{m}^{-17/3}, & r_{\mathrm{diff}} < l_0, \\ 4.7\times 10^{15}\,\mathrm{m}^{-17/3}, & r_{\mathrm{diff}} > l_0. \end{cases}$$

- If the temporal smearing observed in FRB 110220 is intergalactic this implies (for these lines of sight):

$$\mathrm{SM}_{\mathrm{eff}} = (1+z_L)\left(\frac{D_{\mathrm{eff}}}{1\,\mathrm{Gpc}}\right)^{-1}\begin{cases} 3.4\times 10^{16}\left(\frac{l_0}{1\,\mathrm{AU}}\right)^{-1/3}\,\mathrm{m}^{-17/3}, & r_{\mathrm{diff}} < l_0, \\ 1.8\times 10^{16}\,\mathrm{m}^{-17/3}, & r_{\mathrm{diff}} > l_0. \end{cases}$$

J1819 is unique

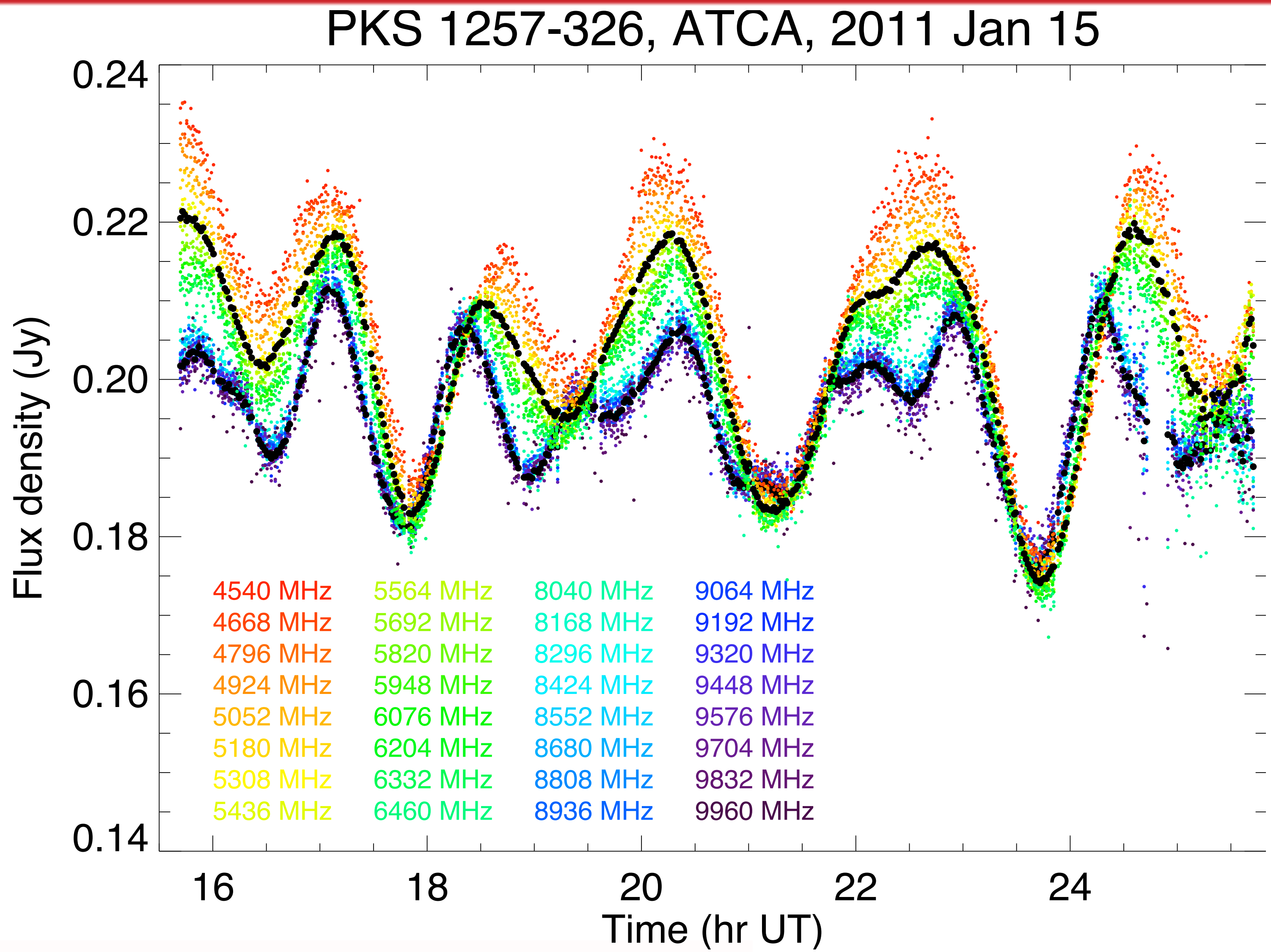
The MicroArcsecond Scintillation-Induced Variability survey

Bignall, Jauncey, Kedziora-Chudczer, Lovell, Macquart, Rickett

- Survey for intra-day variability in 525 compact, flat/inverted-spectrum sources @ 4.8 GHz using VLA in 5 sub-arrays
- 4 x 3-day epochs spaced throughout a year (+ additional followup session) to eliminate annual-cycle selection effects
- **>56% of all sources exhibited IDV in at least one of the four epochs (accounting for false positives)**
- **Uniqueness: no more sources like J1819 found!**

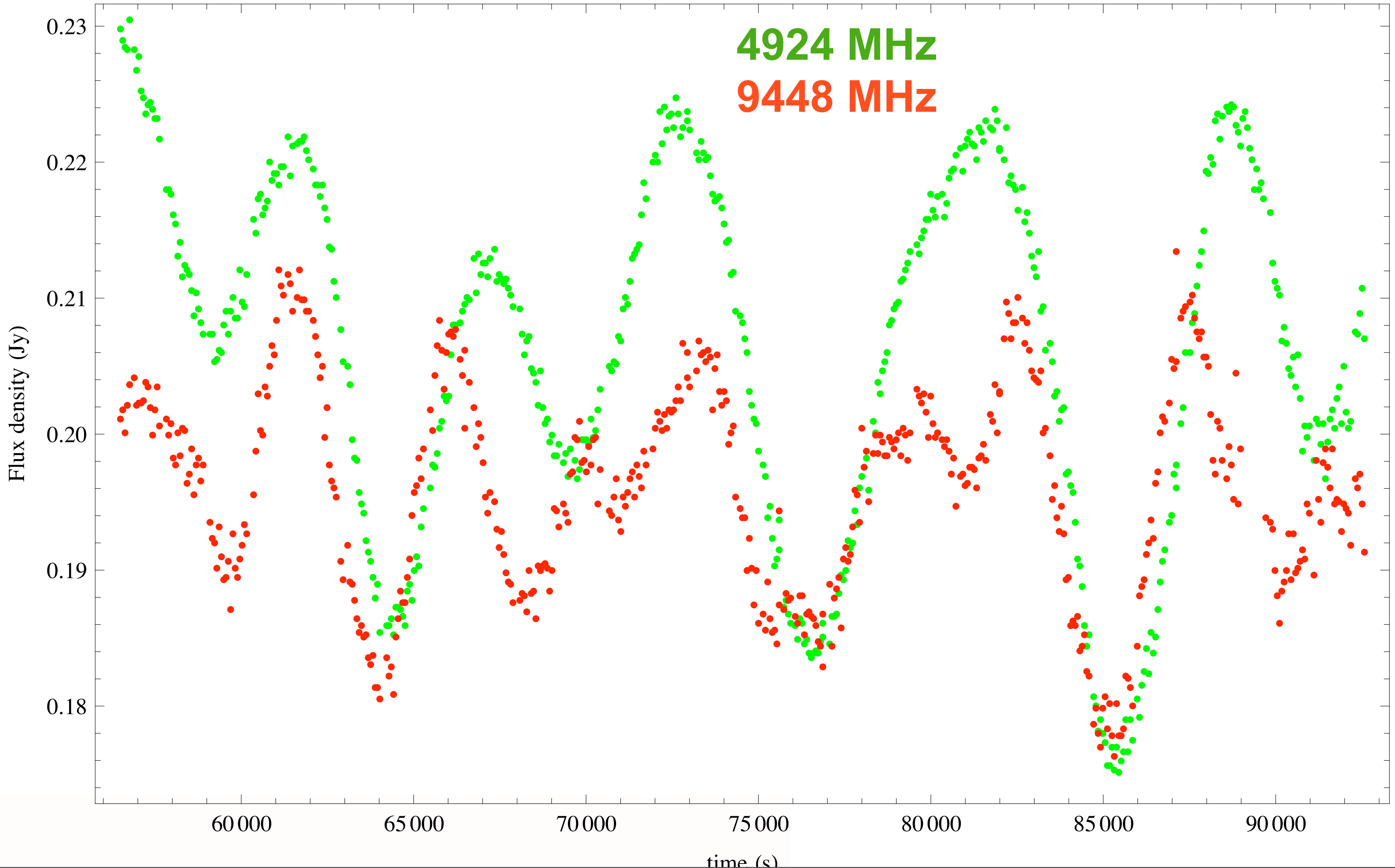
Lovell et al. 2003 & 2008

µas structure of another IHV

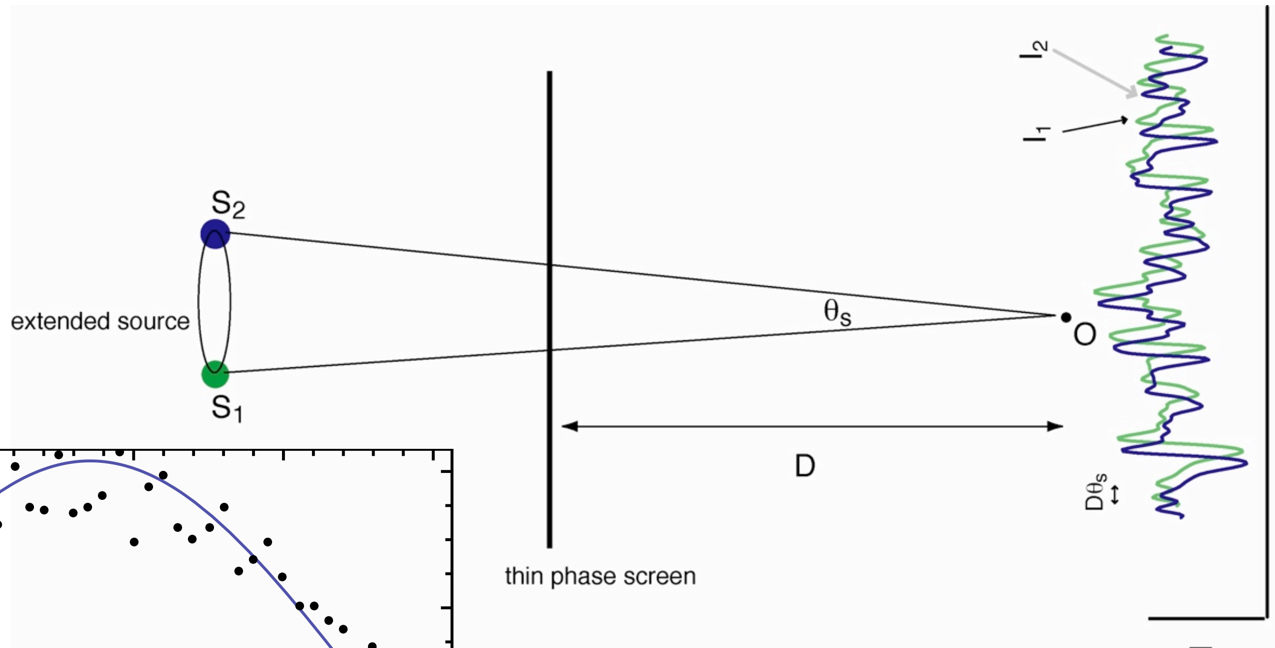


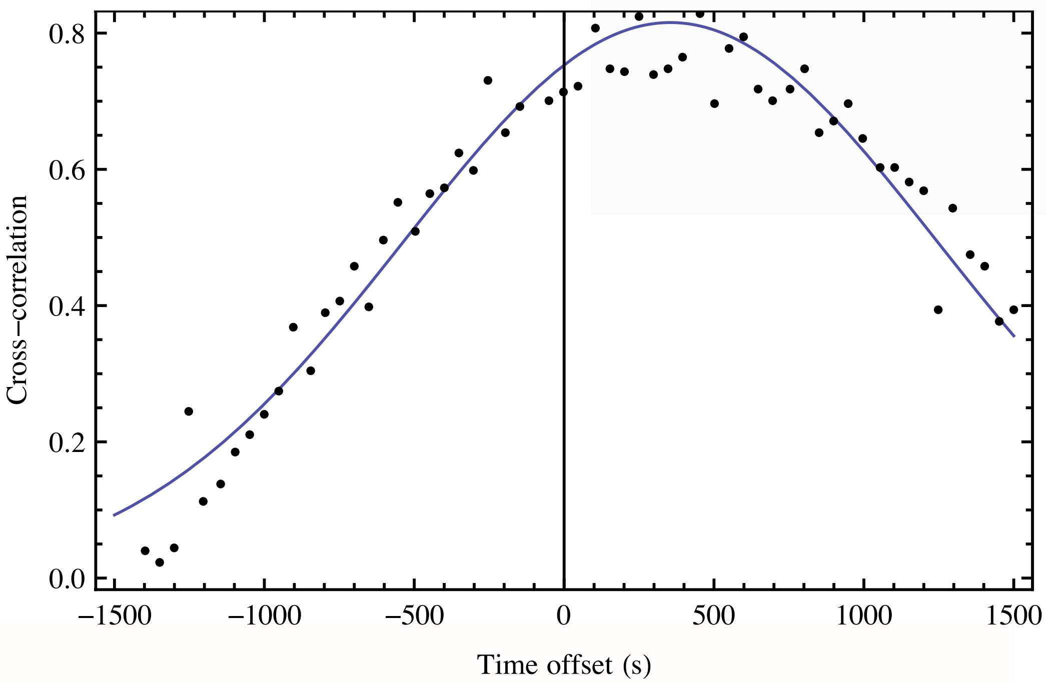
Macquart, Godfrey, Bignall & Hodgson 2013

High Frequencies First



What's happening here?





Cross-correlation between 4540 and 8040 MHz lightcurves. The variations at 8040 MHz lead.

The Core Shift

$$\Delta t(\nu_1,\nu_2) \propto \left| [\theta(\nu_1) - \theta(\mathrm{core})] - [\theta(\nu_2) - \theta(\mathrm{core})] \right|$$

actually

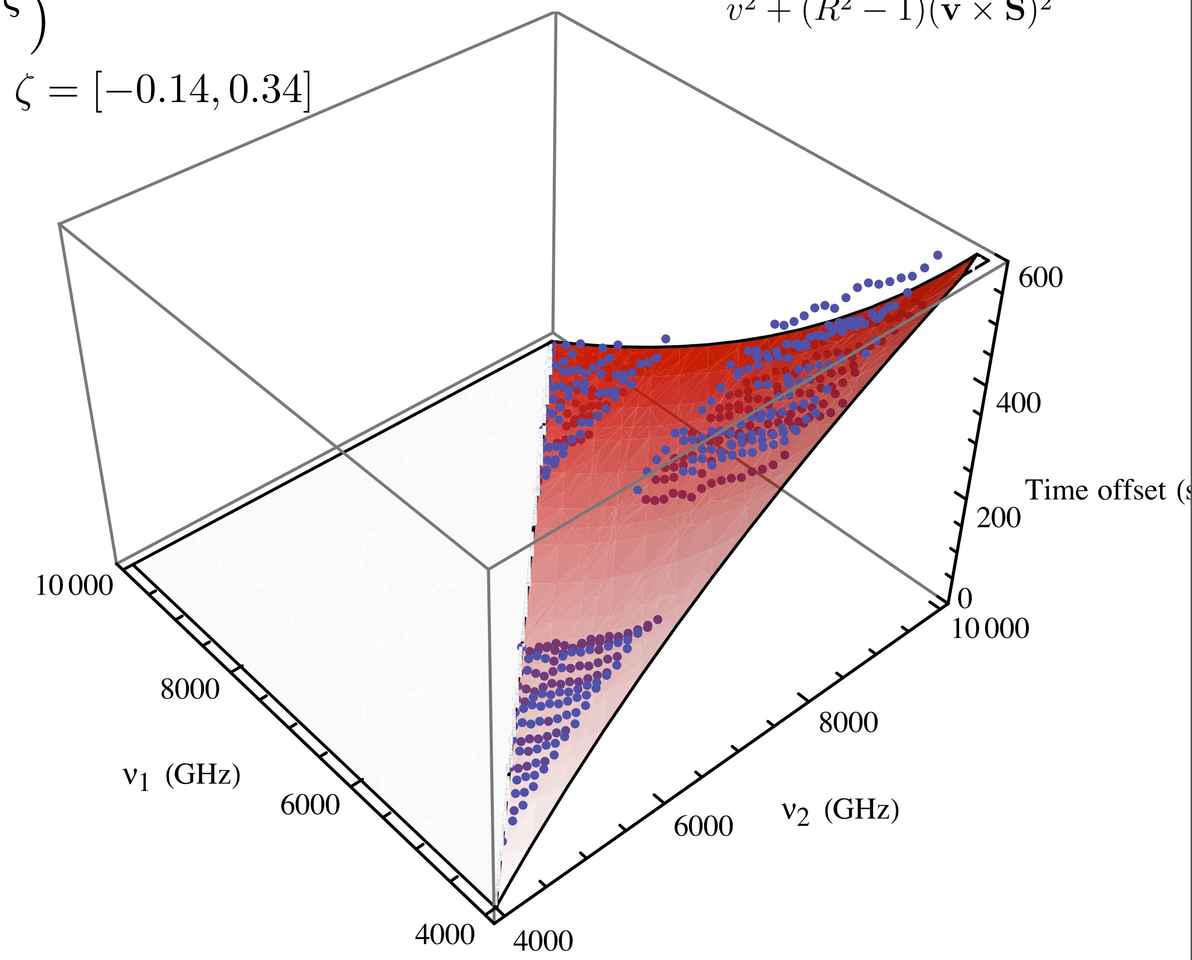
$$\Delta t = -\frac{D\boldsymbol{\theta}\cdot\mathbf{v} + (R^2-1)(D\boldsymbol{\theta}\times\hat{\mathbf{S}})(\mathbf{v}\times\hat{\mathbf{S}})}{v^2 + (R^2-1)(\mathbf{v}\times\hat{\mathbf{S}})^2}$$

$$\Delta t(\nu_1,\nu_2) = K(\nu_1^{-\zeta} - \nu_2^{-\zeta})$$

$\zeta = 0.10$ with 99% confidence interval $\zeta = [-0.14, 0.34]$

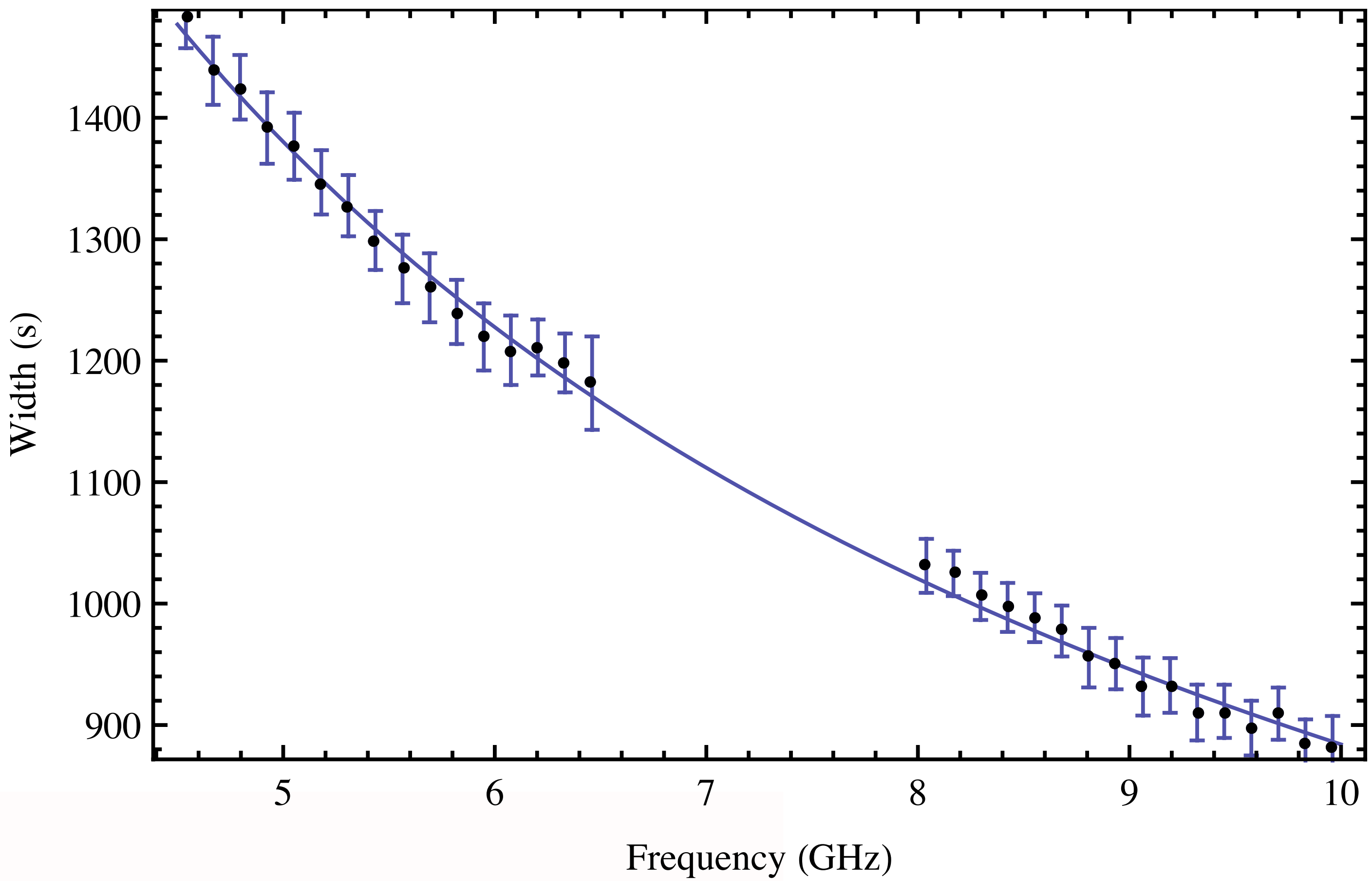
We measure angles to a precision of below
1 as=8.5 mpc or ~90 R_S

Most VLBI measurements of other AGN show ζ=1

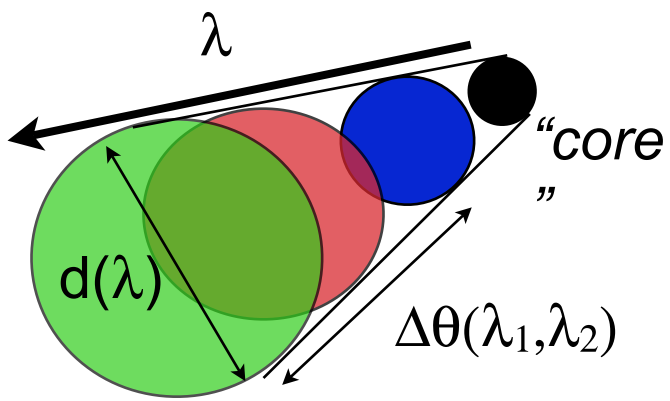


Source Angular Size

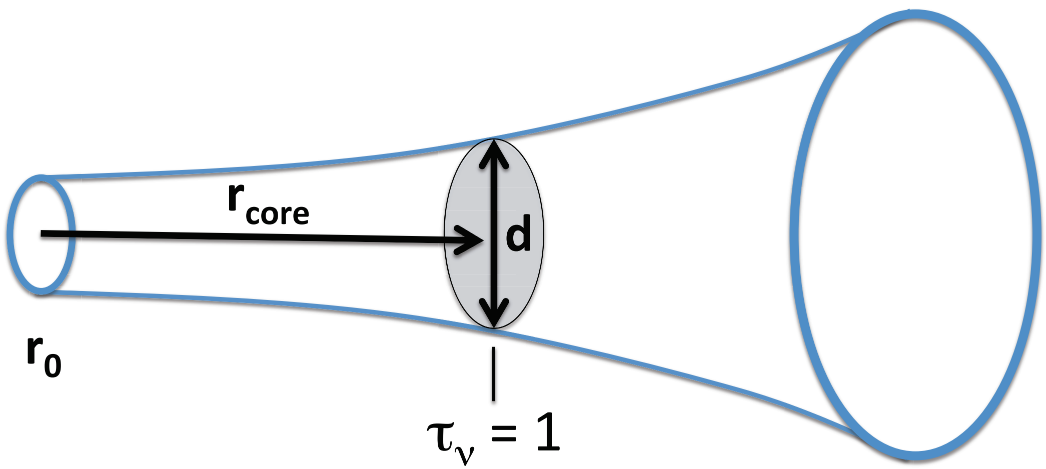
$$\theta_{\rm src}(\nu) = 64 \left(\frac{\nu}{9.96\,\rm GHz}\right)^{-0.64} \left(\frac{D}{10\,\rm pc}\right)^{-1} \mu\rm as$$



Jet Structure



The observer sees the τ=1 surface, and this moves outward with wavelength



$$r_{core} \propto \nu^{-1/k_r} : k_r > 3$$

$$d \propto r_{core}^{n_d} : n_d > 1.8$$

Implications

- Scintillation measures the core-shift to 8 milliparsec precision
    - Standard self-similar jet in equipartition doesn't explain the core shift or scaling of jet opening angle with wavelength (core shift scales as ν^{-1})
    - Free-free absorption unlikely (no evidence for a high rotation measure)
- We instead consider a model in which the jet traverses a steep pressure gradient of the form $p \propto r^{-n_p}$ (i.e. jet is hydrostatically confined)
- Model can explain the observed jet properties
    - Steep pressure gradient may explain a long-standing mystery as to why IDV sources with such high Lorentz factors remain compact enough to scintillate over periods of years (i.e. don't just expand and stop scintillating).

Conclusions

- J1819 may have stopped scintillating, but the nature of its hyperturbulent scattering remains connected to many puzzles relating to ISM turbulence
    - Connection to ESEs and pulsar scattering in hyperturbulent regions?
- J1819 and PKS1257 delivering on promise of probing AGN micro-arcsecond (millipc) structure
- Hydrostatic confinement keeps these sources compact?
- Will another source near J1819 start showing similarly fast variations within the next few years?