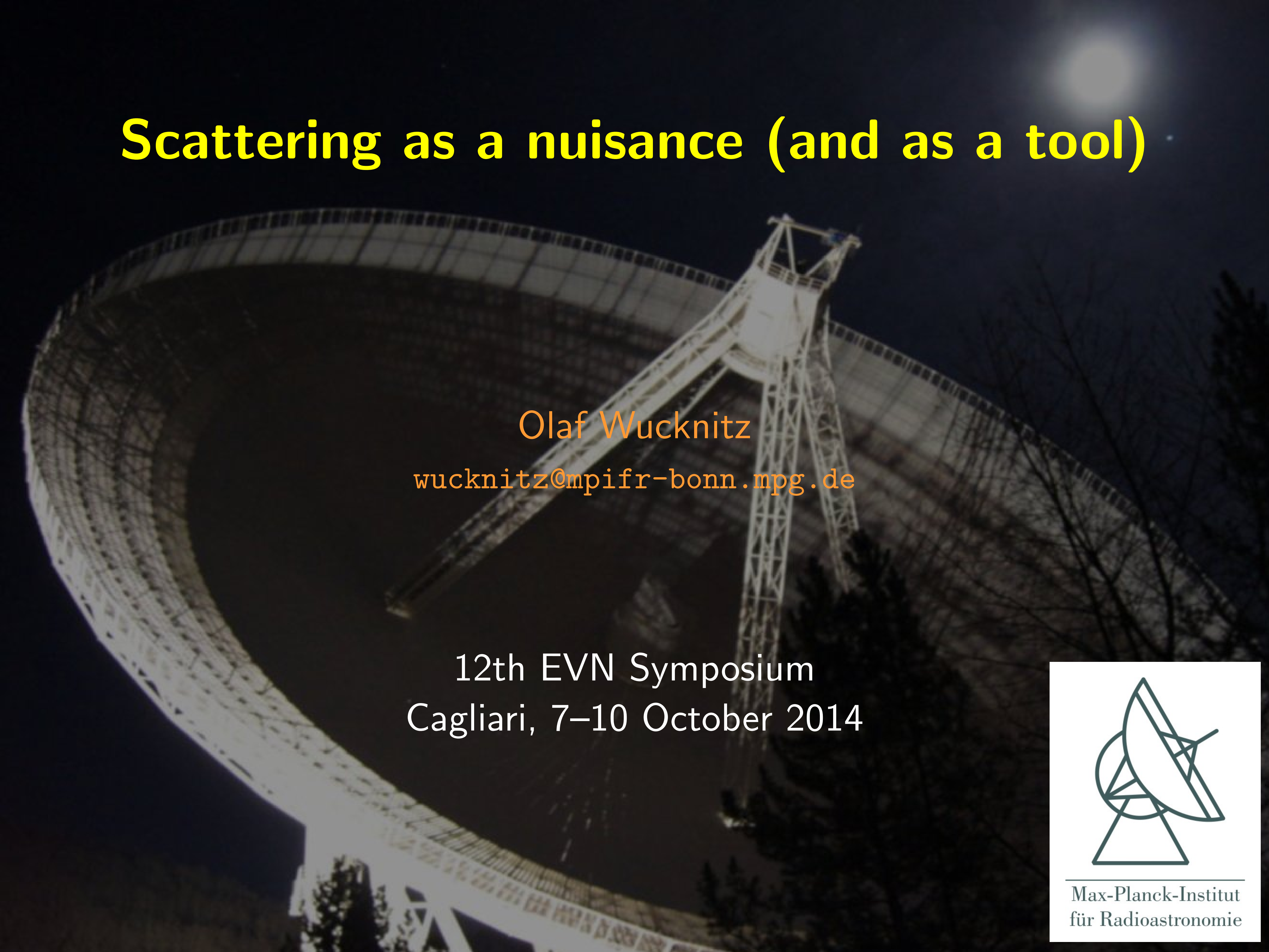

Scattering as a nuisance (and as a tool)

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Max-Planck-Institut für Radioastronomie

Scattering as a nuisance (and as a tool)

- **nuisance**
  - ⋆ pulsars in centre of Milky Way?
  - ⋆ a magnetar near the GC
  - ⋆ temporal and angular broadening
  - ⋆ a one-baseline VLBI experiment
  - ⋆ aim
    - ∗ scattering properties
    - ∗ distance of screen
- tool
  - ⋆ extreme resolution via scintellometry
  - ⋆ use scattering disk as interferometer

⇝ low-frequency VLBI

Motivation

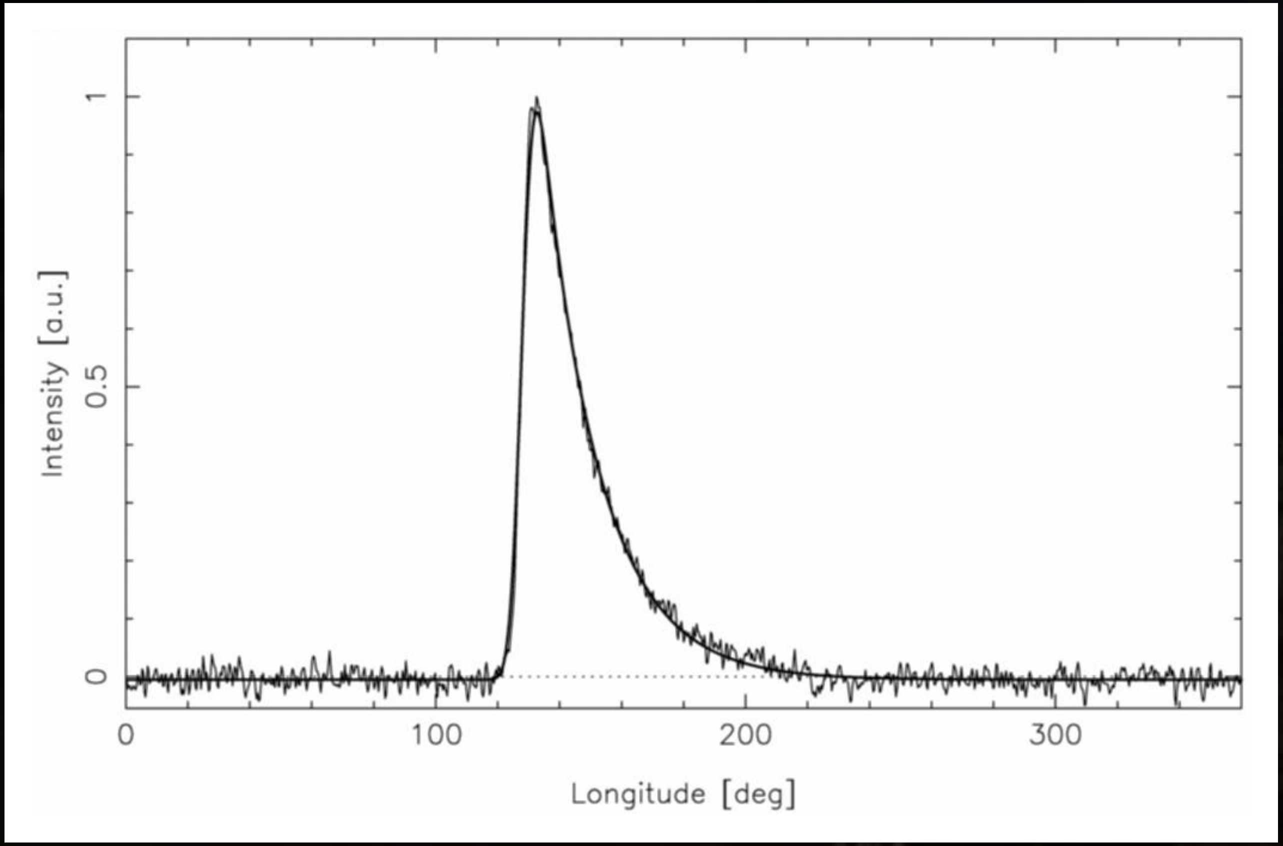
- How to test General Relativity?
  - ⋆ need extreme gravity $\rightsquigarrow$ black hole
  - ⋆ precise measurements $\rightsquigarrow$ time $\rightsquigarrow$ pulsar

- Where to find them?
  - ⋆ black hole in GC, $M \approx 4 \cdot 10^6\,\mathrm{M}_\odot$
  - ⋆ high density of stars $\rightsquigarrow$ there should be many pulsars in close orbits!

- What can be done? *[Liu et al. (2012)]*
  - ⋆ precision mass, spin (cosmic censorship), quadrupole moment (no hair theorem), perturbations, . . .
  - ⋆ mass distribution around centre

The problem: scatter broadening of pulses

B1815–14 at 1.4 GHz



[Löhmer et al. (2001)]

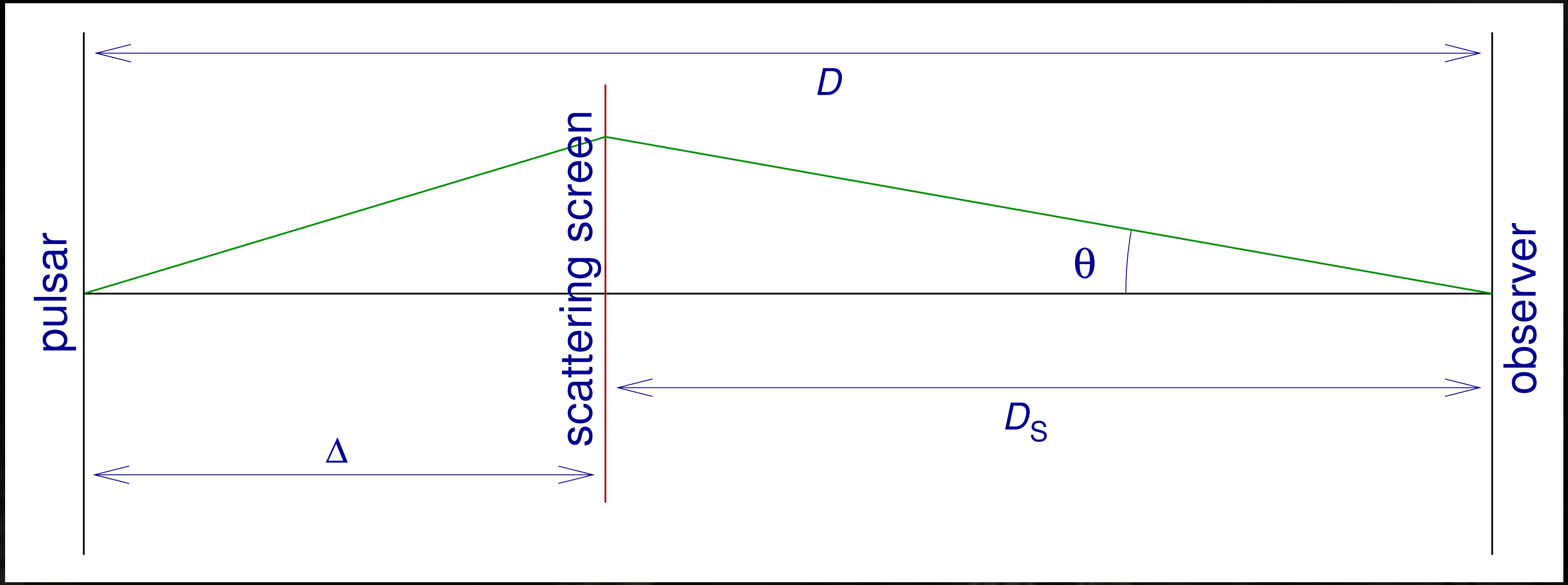
- stronger at lower frequencies: $\tau \propto \lambda^4$ or $\lambda^{4.4}$
- strong dependence on line of sight (GC worst)
- can wash out pulses if $\tau \gtrsim P$

How many have we spotted so far?

. . . nearly, ooh, nearly one.   Er, call it none.

- rough estimate: $\tau \sim (\text{few } 100\,\text{sec}) \left(\frac{f}{\text{GHz}}\right)^{-4}$
- go to higher frequencies (despite steep spectrum)
- *Macquart et al. (2010)*
  15 GHz with GBT within 1–2 pc
  should have found ~ 90, found 0
- *Eatough (2013), MRU2013 and priv. comm.*
  19 GHz with Effelsberg within 1–2 pc
  total time 1 year, integration time ~2 days
  should have found very many, found 0

Interstellar scattering: geometry



$$c\tau = \frac{1}{2}\theta^2 D' \qquad D' = \frac{D\,(D-\Delta)}{\Delta} \qquad \text{diverges for } \Delta \to 0$$

- screen close to pulsar: large τ/θ^2
- screen close to observer: small τ/θ^2

Where is the screen?

GC Scattering screen

- for Sgr A*: $$2\theta = 950\,\mathrm{mas}\left(\frac{f}{\mathrm{GHz}}\right)^{-2}$$

- distance from GC: fit to scattering sizes, DM, free-free, . . . *[Lazio & Cordes (1998)]*

$$\Delta = \left(133^{+200}_{-80}\right)\,\mathrm{pc} \quad \rightsquigarrow \quad \tau = 150\,\mathrm{sec}\left(\frac{f}{\mathrm{GHz}}\right)^{-4}$$

- “somewhere in the middle”

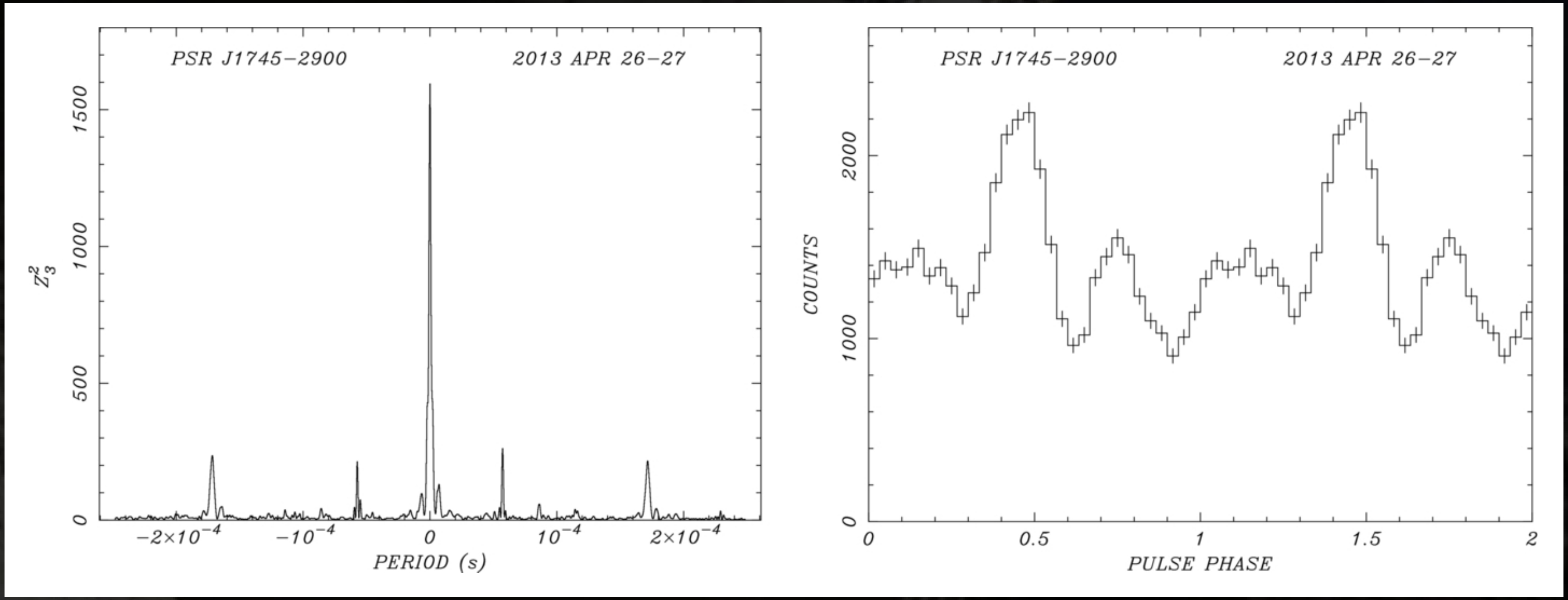
$$\Delta = \frac{D}{2} \quad \rightsquigarrow \quad \tau = 2\,\mathrm{sec}\left(\frac{f}{\mathrm{GHz}}\right)^{-4}$$

$\rightsquigarrow$ difficult/impossible to find pulsars at low frequencies

Then suddenly. . .

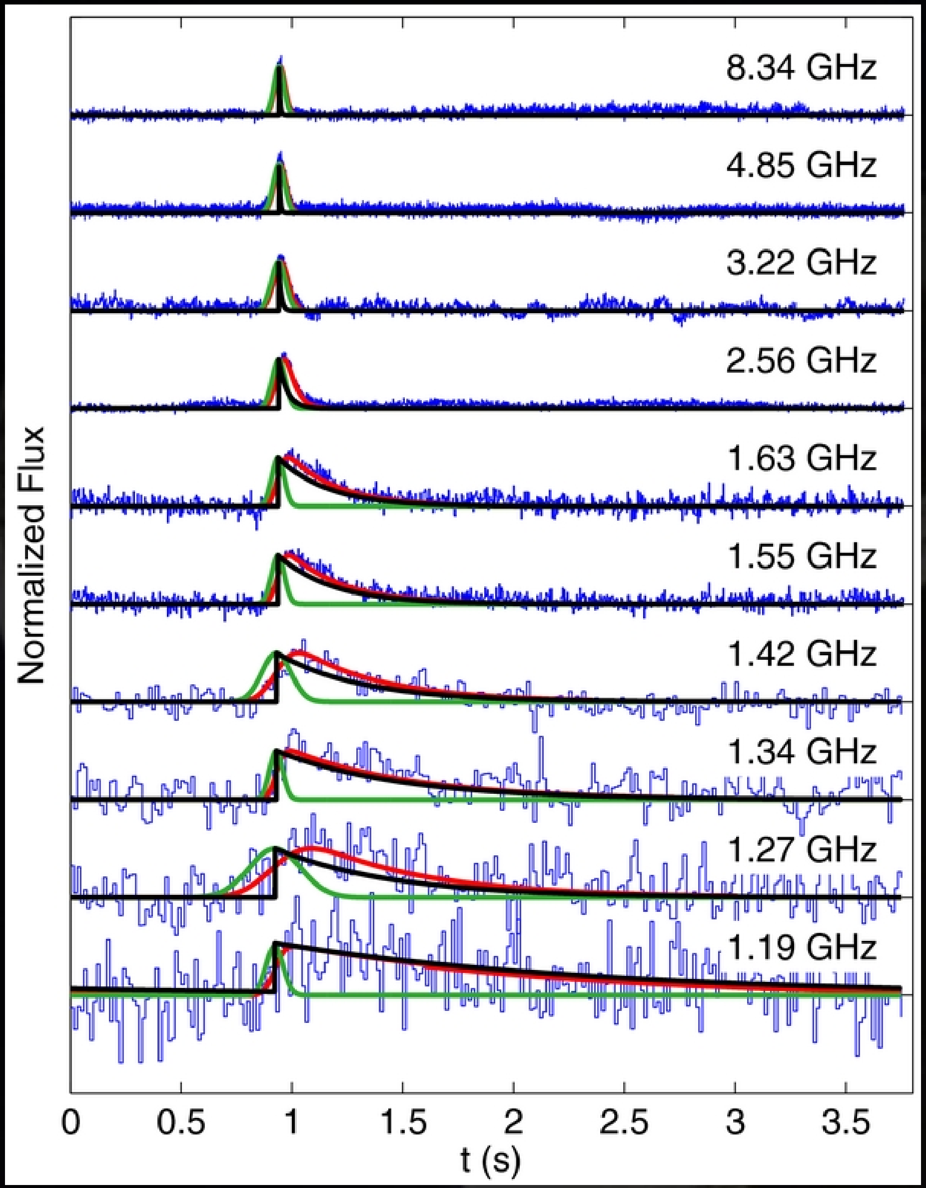
- Swift X-ray flare 26th April 2013 in Sgr A* area
- NuSTAR finds 3.76 sec period, probably magnetar

[Mori et al. (2013)]



- Chandra: ca. 3″ from Sgr A*
- radio search begins: first detection 2nd May (Effelsberg) *[Eatough et al. (2013), ATel 5040]*

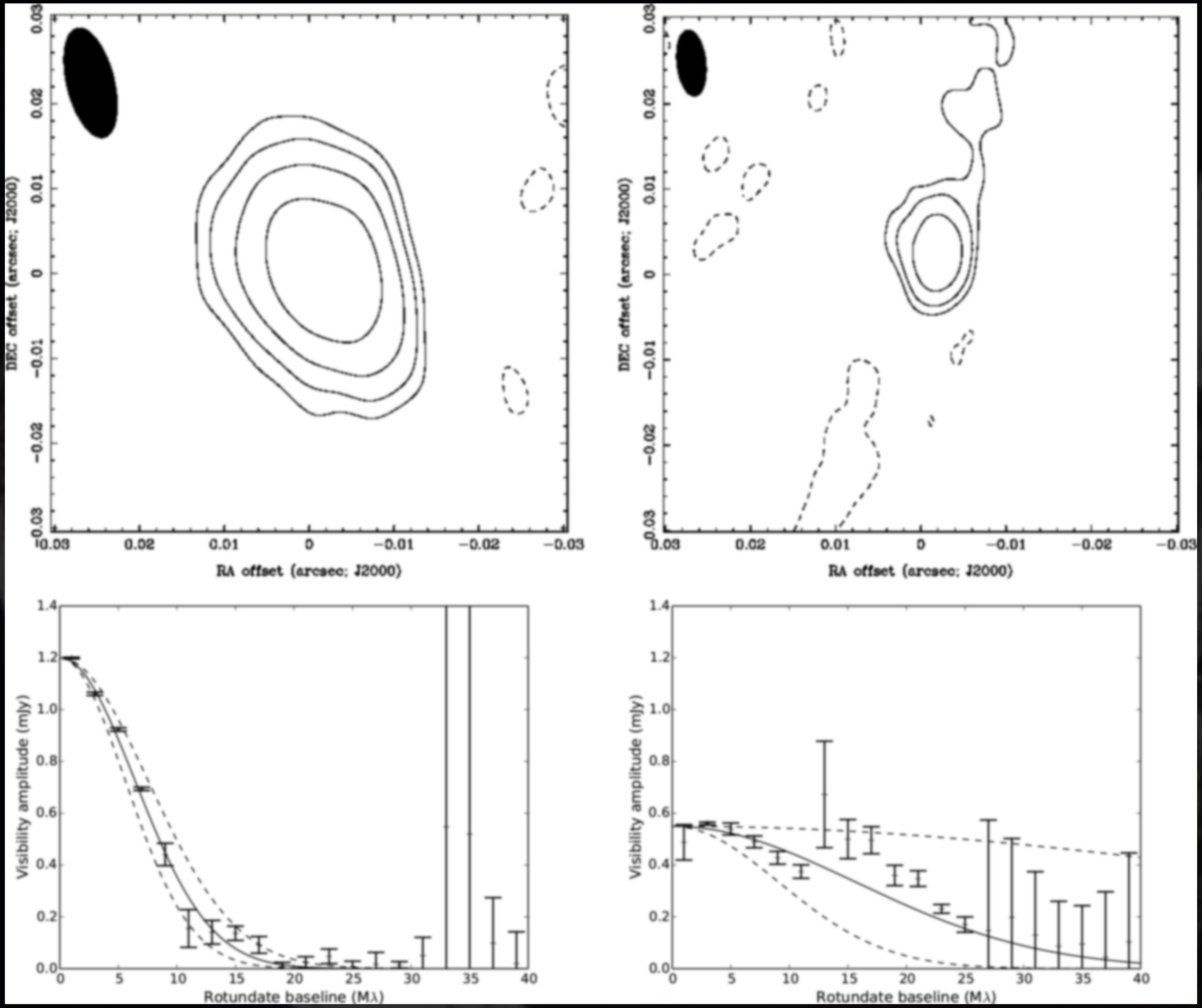
Temporal scatter broadening of J1745–29



[Spitler et al. (2014)]

- fits to averaged profiles and single pulses
- including intrinsic width
- $$\tau = 1.3\,\mathrm{sec} \left(\frac{f}{\mathrm{GHz}}\right)^{-3.8}$$
- compare to 150 or 2 sec
- why so much less?

Angular scatter broadening of J1745–29



- VLBA+VLA at 8.7 and 15.4 GHz
- $16.1 \times 8.8\,\mathrm{mas}^2$ and $5.4 \times 3.7\,\mathrm{mas}^2$
- consistent with Sgr A*

$$2\theta \approx 980\,\mathrm{mas}\,\left(\frac{f}{\mathrm{GHz}}\right)^{-2}$$

[Bower et al. (2014)]

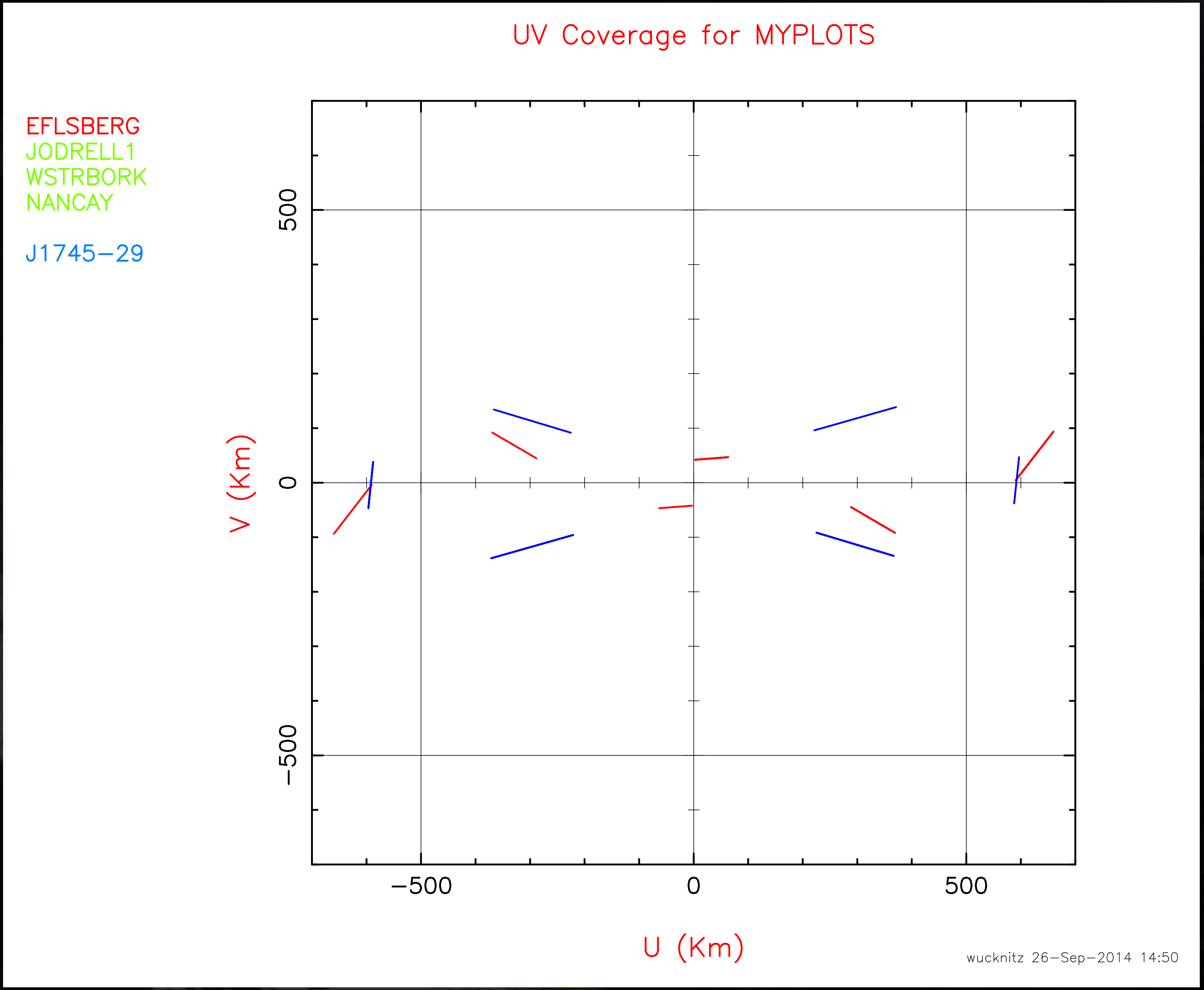
- combine τ and θ: $\Delta = (5.9 \pm 0.3)\,\mathrm{kpc}$ if same thin screen!

Testing the 'one thin screen' model

- so far: compared only $< \tau >$ and $< \theta^2 >$ averaged over profile
- can do this for slices: measure $\theta(\tau)$ or profile(θ)
- only for thin screen: $\tau \propto \theta^2 D'$ (expanding ring)
- allow resolving τ: 1.4–2 GHz
- sizes: 500–250 mas
- baselines: 90–125 km
- sensitivity: LEAP (Large European Array for Pulsars)
  - ⋆ Effelsberg, Lovell, Nancay, Westerbork, now also Sardinia
  - ⋆ pulsar backends: 8-bit sampling
  - ⋆ data distribution logistics
- observed 9th November 2013

Thanks to LEAP group!

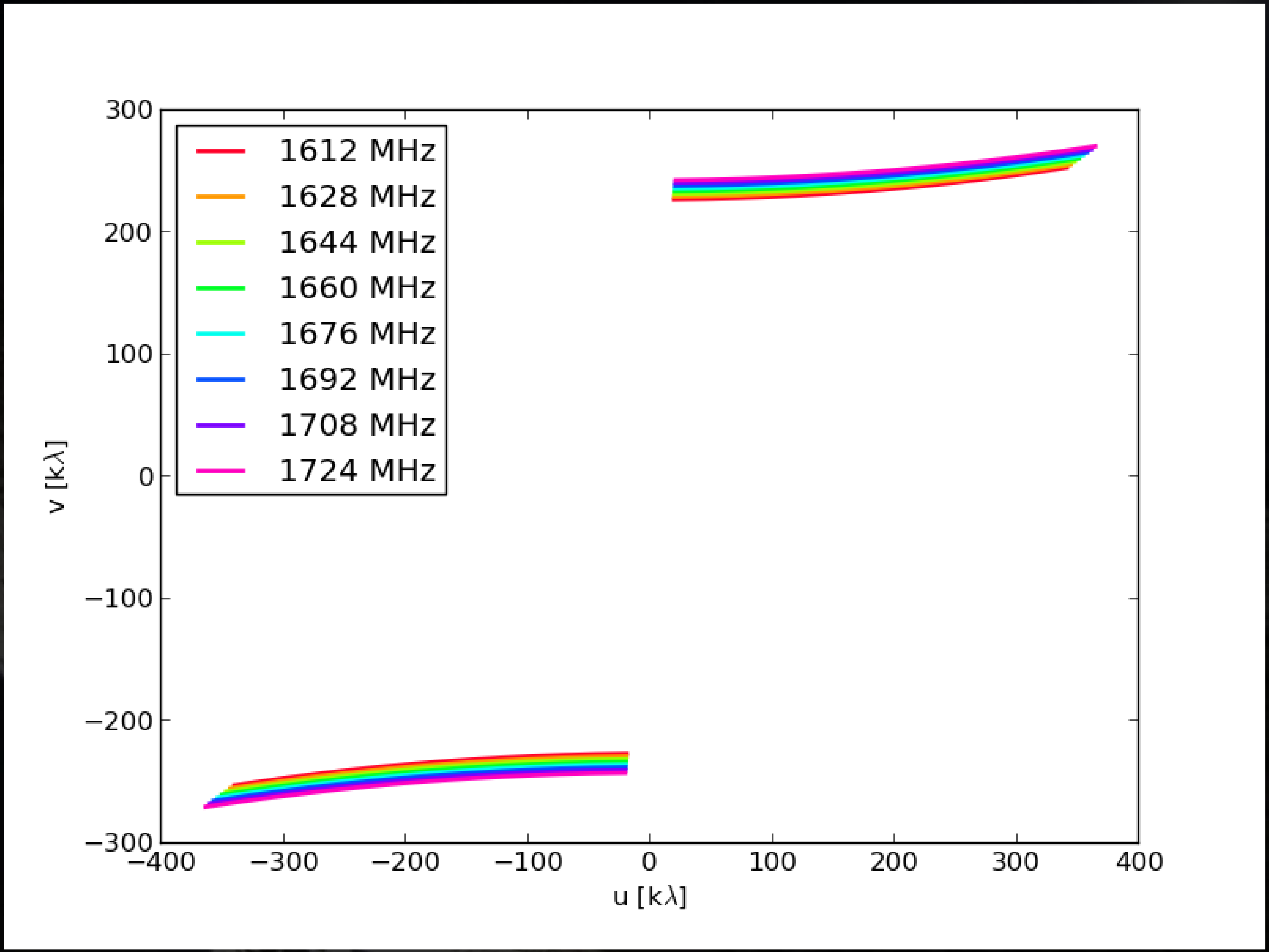
LEAP uv coverage



Observations

- 9th Nov 2013 13:48–14:55 plus calibrators
- frequency range 1604–1732 MHz in 8 bands (RFI in lower 2)
- Effelsberg, Lovell, Nancay, Westerbork
- Lovell: lost most data, Nancay: different format
- so far only analysed **Ef–Wb**
  - ⋆ baseline 267 km, projected 42–79 km
  - ⋆ resolution $\sim 0.''9$–$0.''45$
  - ⋆ Ef close to saturation (affects single-dish profile)
    (Ef noise near Sgr A is 8 times higher than normal)
  - ⋆ time offset 409 msec
- use Sgr A* as in-beam calibrator only $2.''4$ away

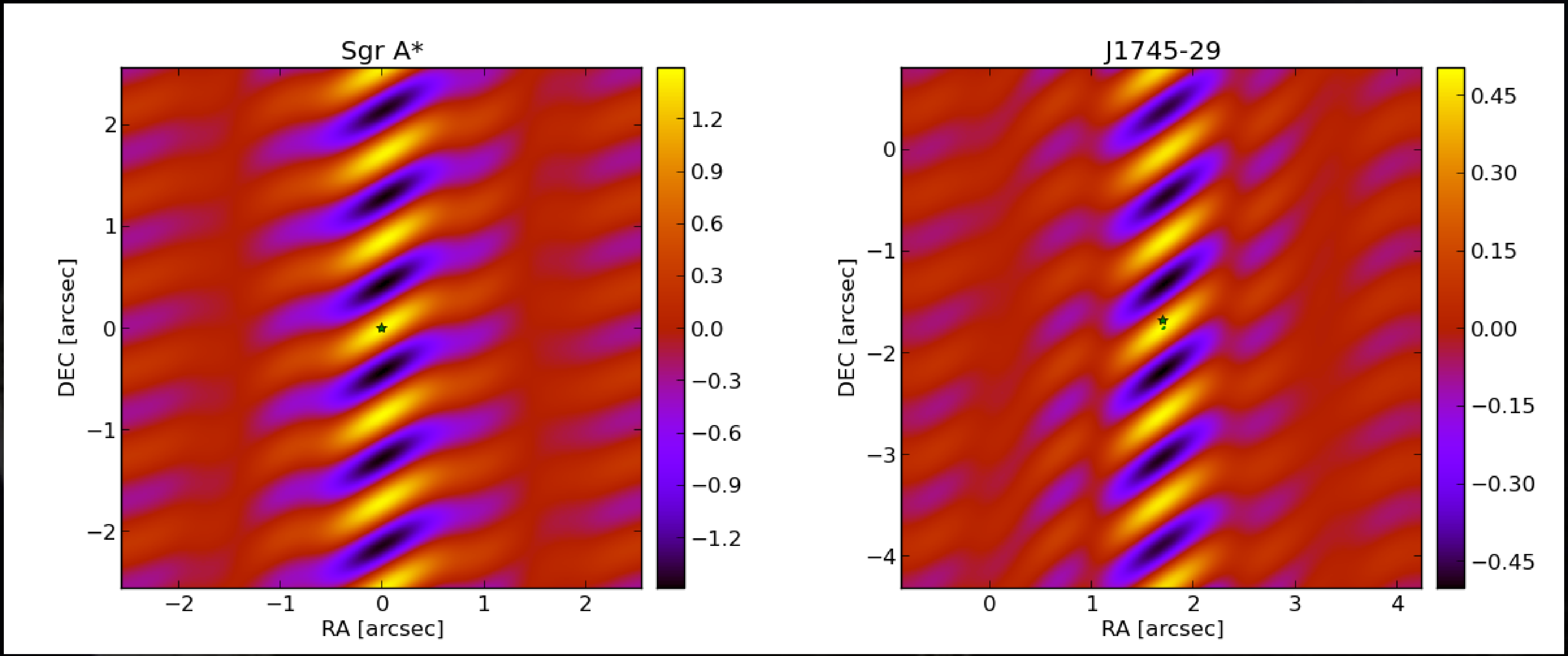
UV coverage Ef-Wb



Correlation, calibration

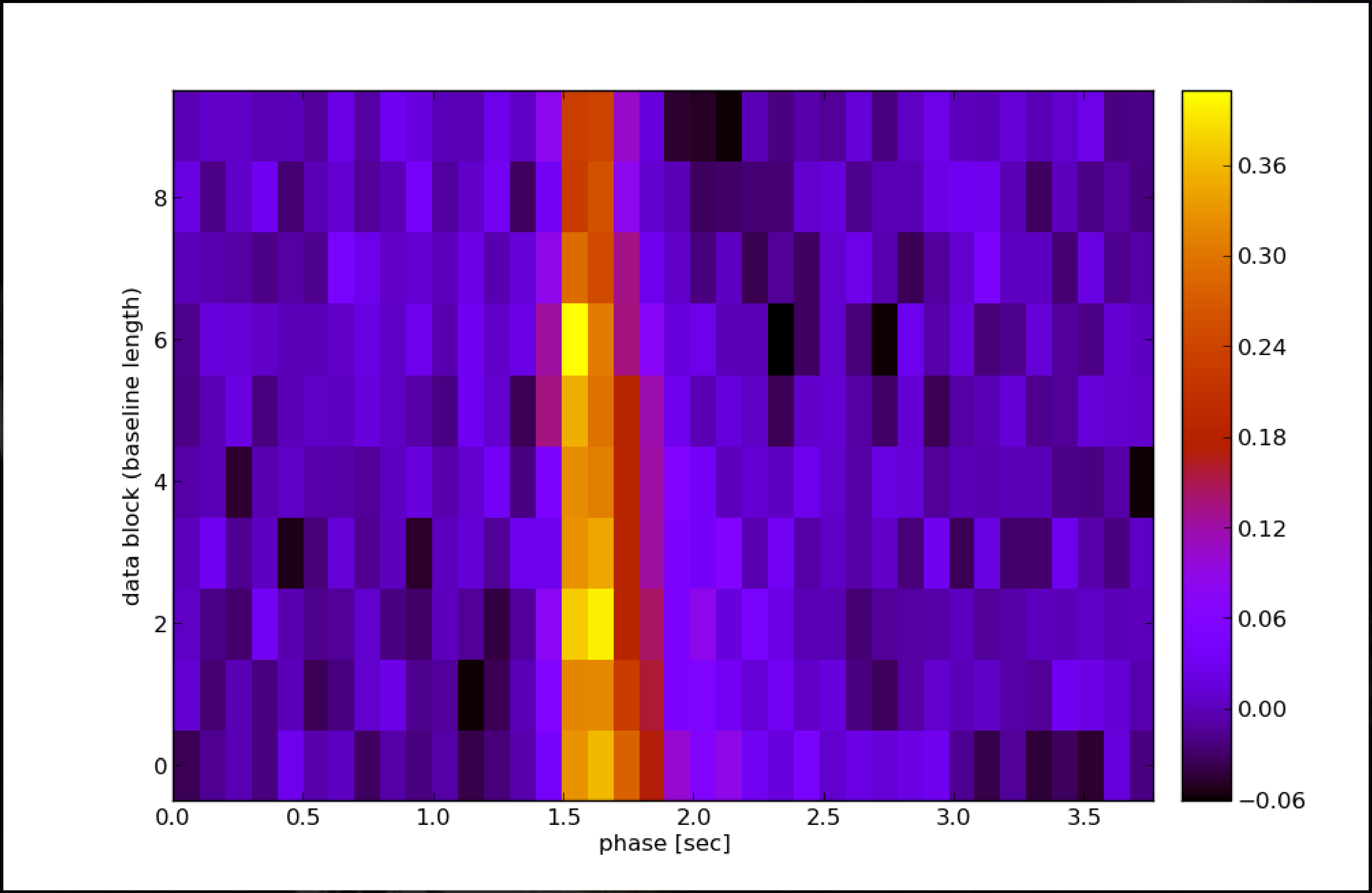
- DADA format, not readable by DiFX (or SFXC)
- used own correlator, binning/gating possible
- convert Wb to circular polarisation
- 3.764 sec period, used bins of 0.005 sec, here 0.1 sec
- fringe-fitting for disp delay, non-disp delay, rates, DFR, orientation
  finally used: delay, rate, phase (and predicted parallactic angle)
- bandpass in amplitude and phase
- gated for Sgr A* or magnetar (with Sgr A* subtracted)
- consistent offset, finally used Sgr A* for calibration, then phase shift to magnetar

Gated dirty maps

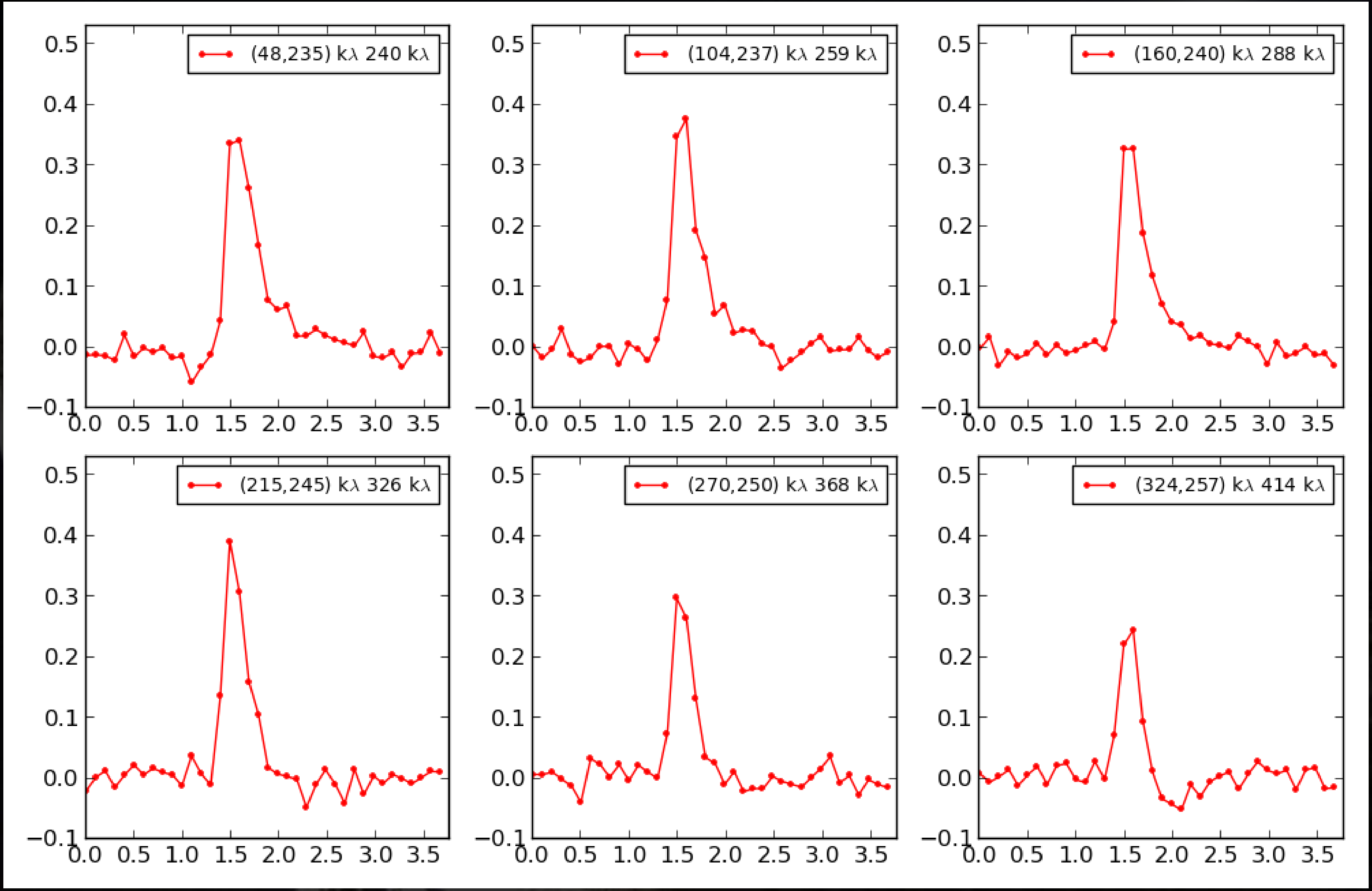


- beam not optimal, but can separate both objects
- Sgr A* extended as expected
- J1745–29 slightly offset from VLBI position
- peak of J1745–29 slightly more compact

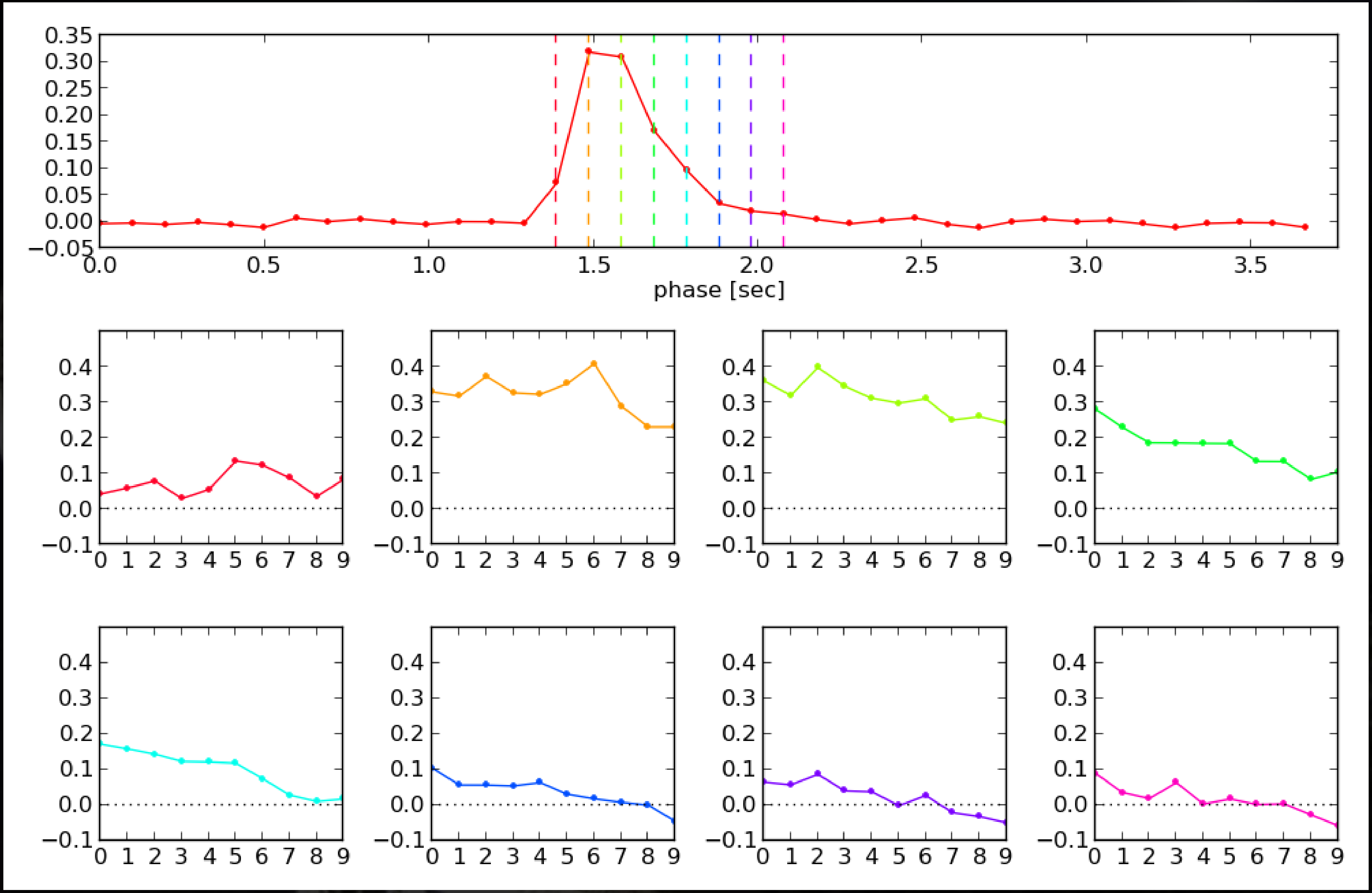
Profile as function of τ and (u, v)



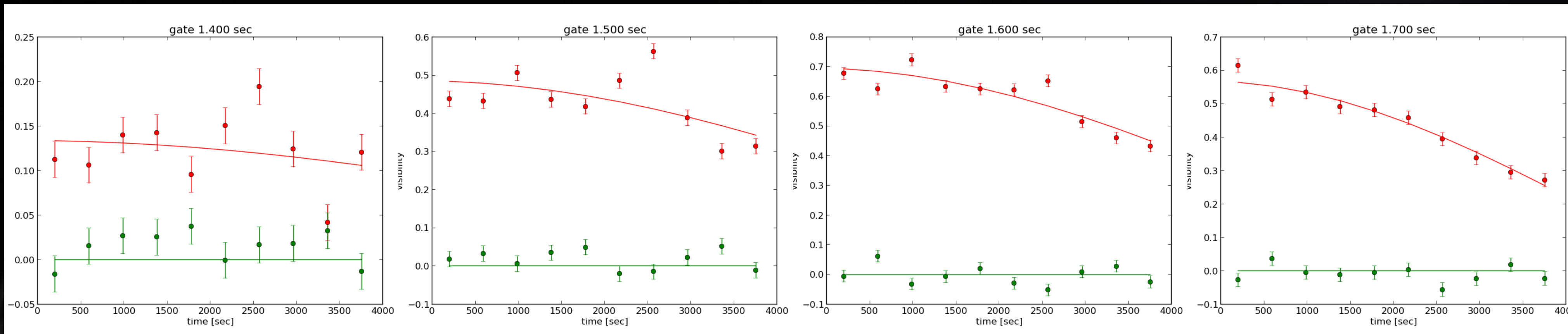
Profiles for different (u, v)

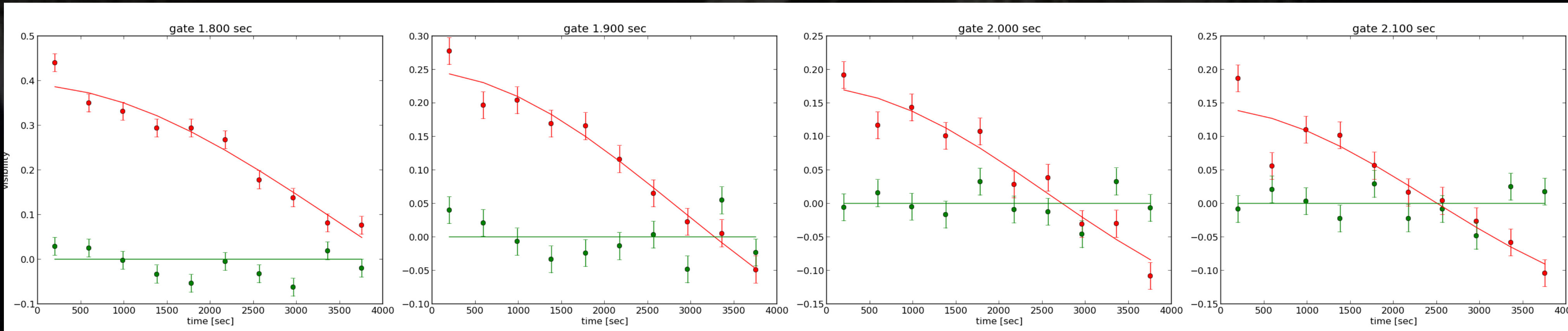


Visibility functions for different τ

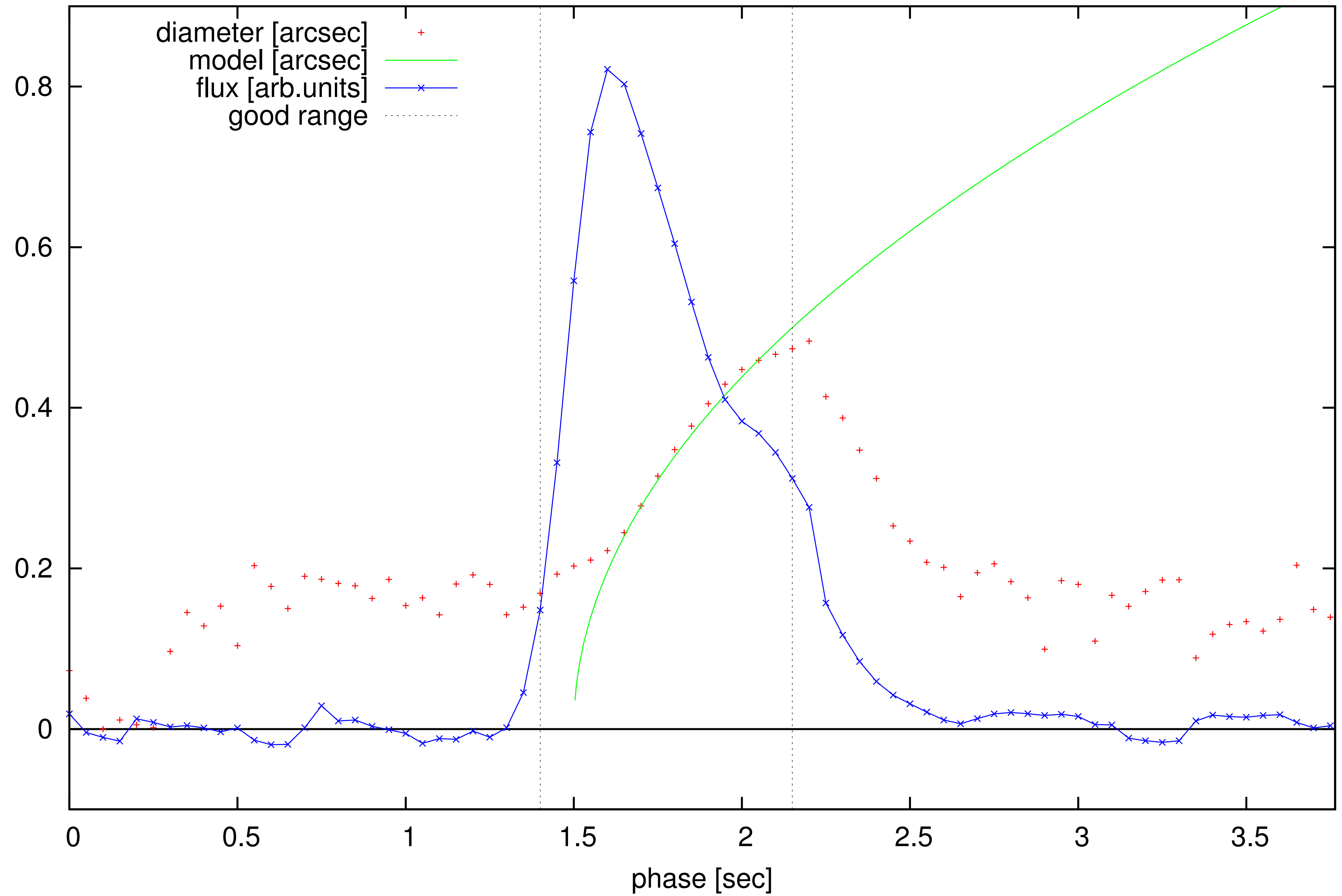


Fits of (uniform circular) rings





Size vs. time (binned)



Distance of scattering screen

Temporal and angular broadening dominated by the same screen!

- $c\tau = \frac{1}{2} D' \theta^2$
- $2\theta = 0\overset{\prime\prime}{.}62 \sqrt{\frac{t}{\mathrm{sec}} - 1.5}$

$\rightsquigarrow$ $D' = 8.85 \cdot 10^{11} c\,\mathrm{sec} = 8.6\,\mathrm{kpc}$

- $D' = \frac{D\,(D - \Delta)}{\Delta}$

$\rightsquigarrow$ $\Delta = \frac{D^2}{D' + D}$

- $D = 8.5\,\mathrm{kpc}$

$\rightsquigarrow$ **$\Delta = 0.50\,D = 4.2\,\mathrm{kpc}$**

Summary

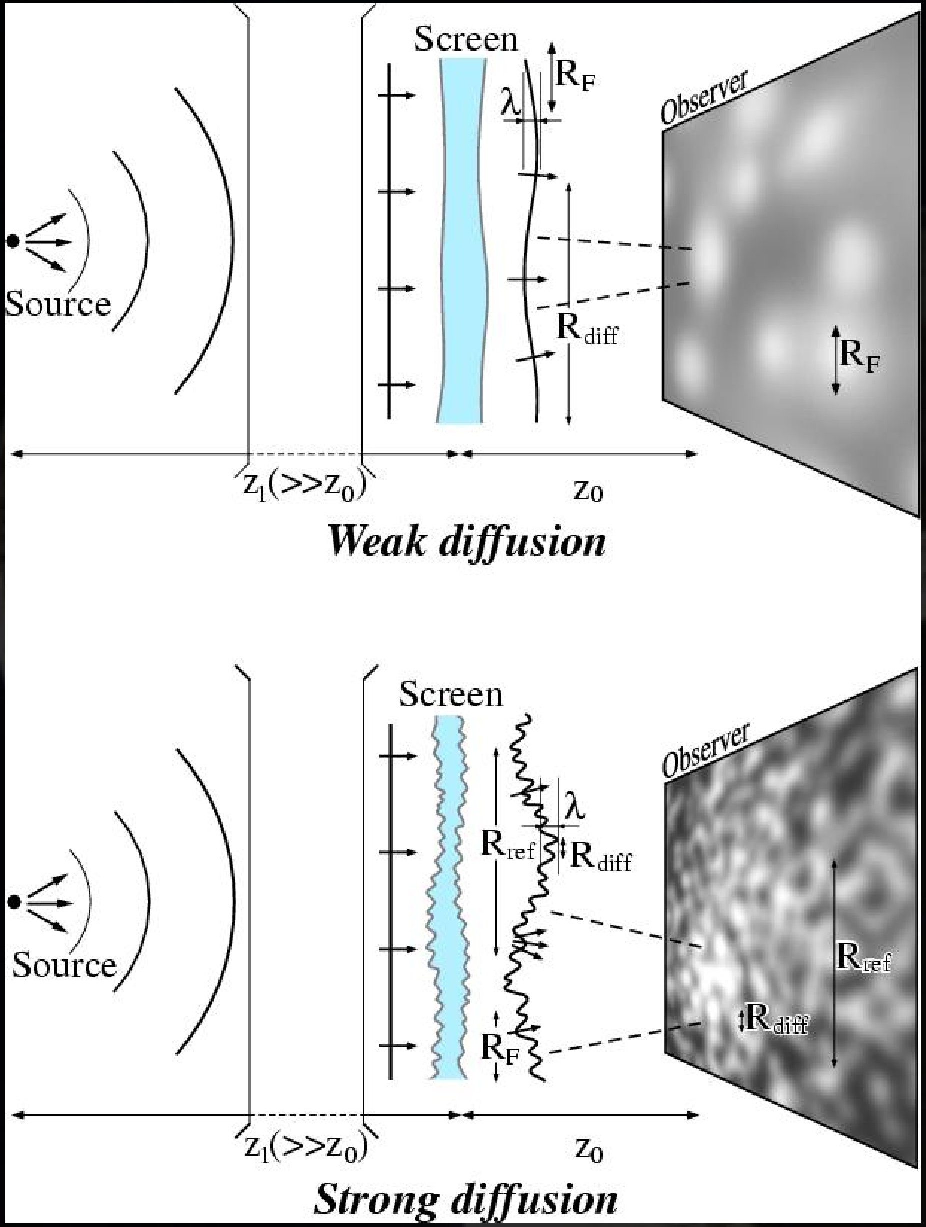
- Sgr A* and J1745–29 have same scattering properties
- temporal and angular broadening from *one* screen
- *preliminary* result $\qquad \Delta = 0.50\,D = 4.2\,\mathrm{kpc}$
  - ⋆ *Lazio & Cordes (1998)* $\qquad 0.13\,\mathrm{pc}$
  - ⋆ *Bower et al. (2014), Spitler et al. (2014)* $\qquad 5.9\,\mathrm{kpc}$
- caveats
  - ⋆ not full time resolution yet (will be done)
  - ⋆ not anisotropic yet (will be done)
  - ⋆ not consistent global fit yet (will be done)
  - ⋆ variability not considered yet (will be done)
  - ⋆ bad uv coverage, will include other baselines

Questions

- inconsistency with models of GC
- why strong scattering close to Sgr A* in projection but 4 kpc away?
- still open: **Where are all the pulsars?**
  - ⋆ line of sight to J1745–29 special (hole in screen)?
  - ⋆ additional scattering *very* close to Sgr A*?
  - ⋆ could be studied with Sgr A* scintillation (prevented by source size)
  - ⋆ evidence for increased broadening (summer 2014)

Thanks to LEAP team, in particular: Cees Bassa, Ramesh Karuppusamy, Kuo Liu; also to Ralph Eatough

Scattering as a tool



[Moniez (2003)]

- turbulent plasma causes delays
- phase fluctuations $\rightsquigarrow$ subimages

$\rightsquigarrow$ scatter-broadening $\theta \propto \lambda^{2.2}$

$\star$ $< \mu$arcsec to $>$arcsec

- subimages interfering

$\rightsquigarrow$ interstellar scintillation

- observed in
  - $\star$ compact AGN, masers
  - $\star$ pulsars

Interstellar scattering interferometry (scintellometry)

- scattering disk $\alpha_1 \propto \lambda^{2.2}$, μarcsec–arcsec

- linear resolution $$d = \frac{\lambda}{\alpha_1}\frac{D-\Delta}{\Delta} \propto \lambda^{-1.2}\frac{D-\Delta}{\Delta}$$

  pulsars 150 MHz–20 GHz: $10 - 10^7$ km

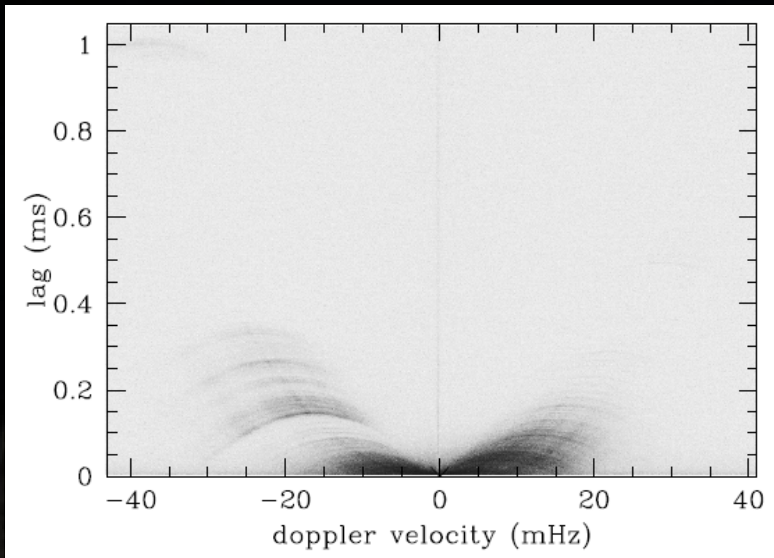
- angular resolution $$\Delta\theta = \frac{\lambda}{\alpha_1}\frac{D-\Delta}{D\Delta} \propto \lambda^{-1.2}\frac{D-\Delta}{D\Delta}$$

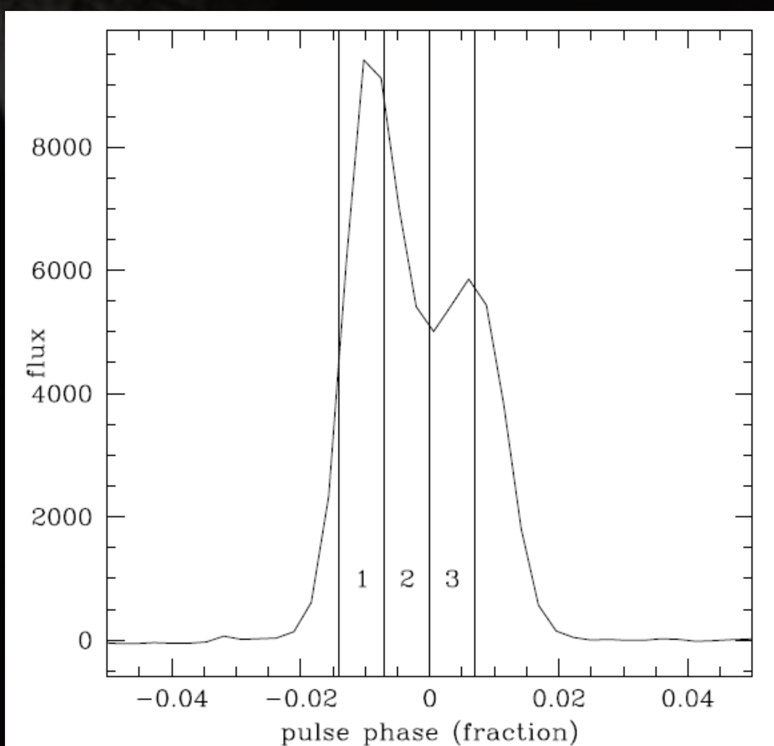
  pulsars 150 MHz–20 GHz: milli-arcsec – pico-arcsec

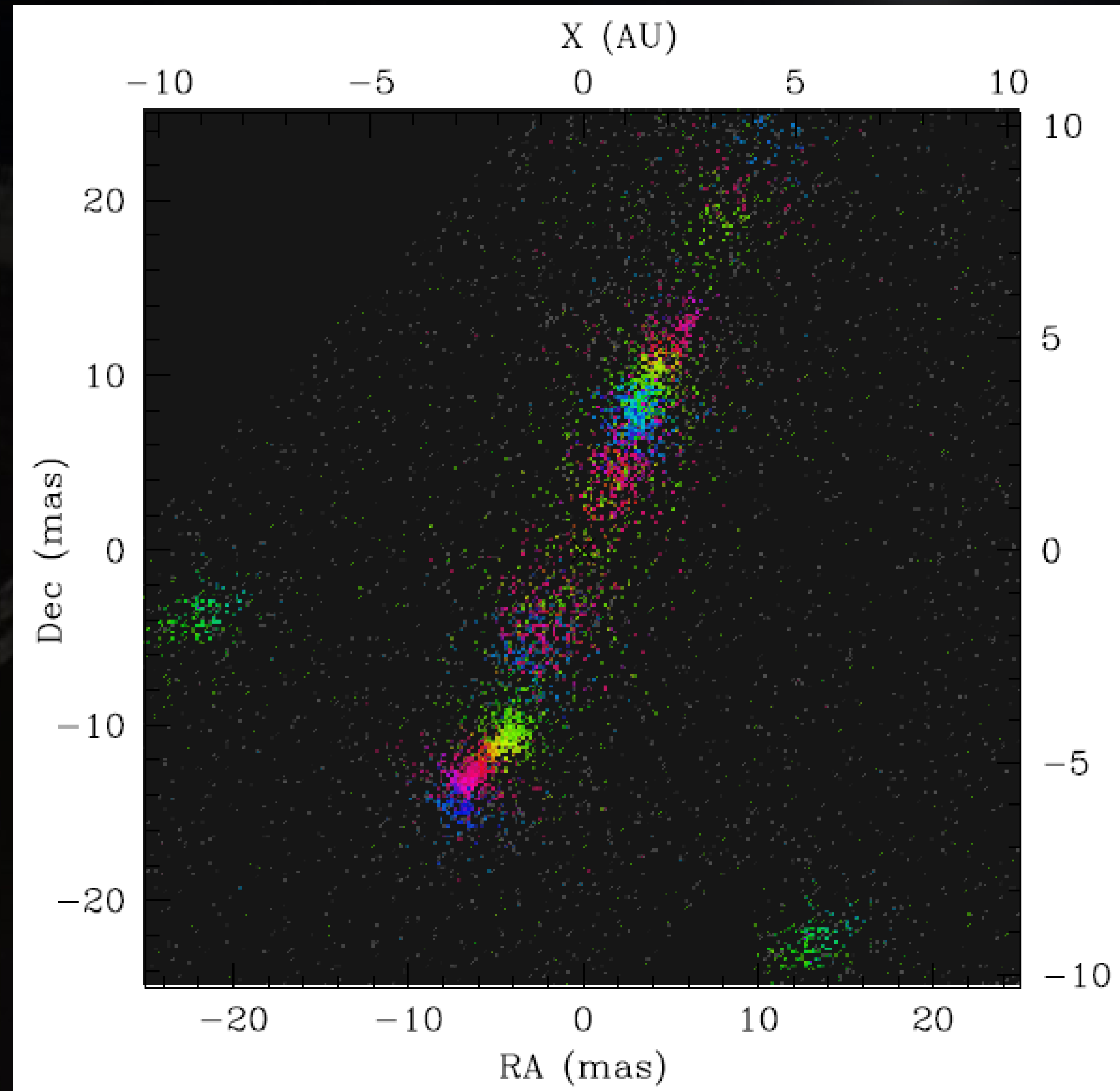
- potentially extreme resolution!

- lower frequencies $\rightsquigarrow$ higher resolution

Scintellometry for pulsar B0834+06

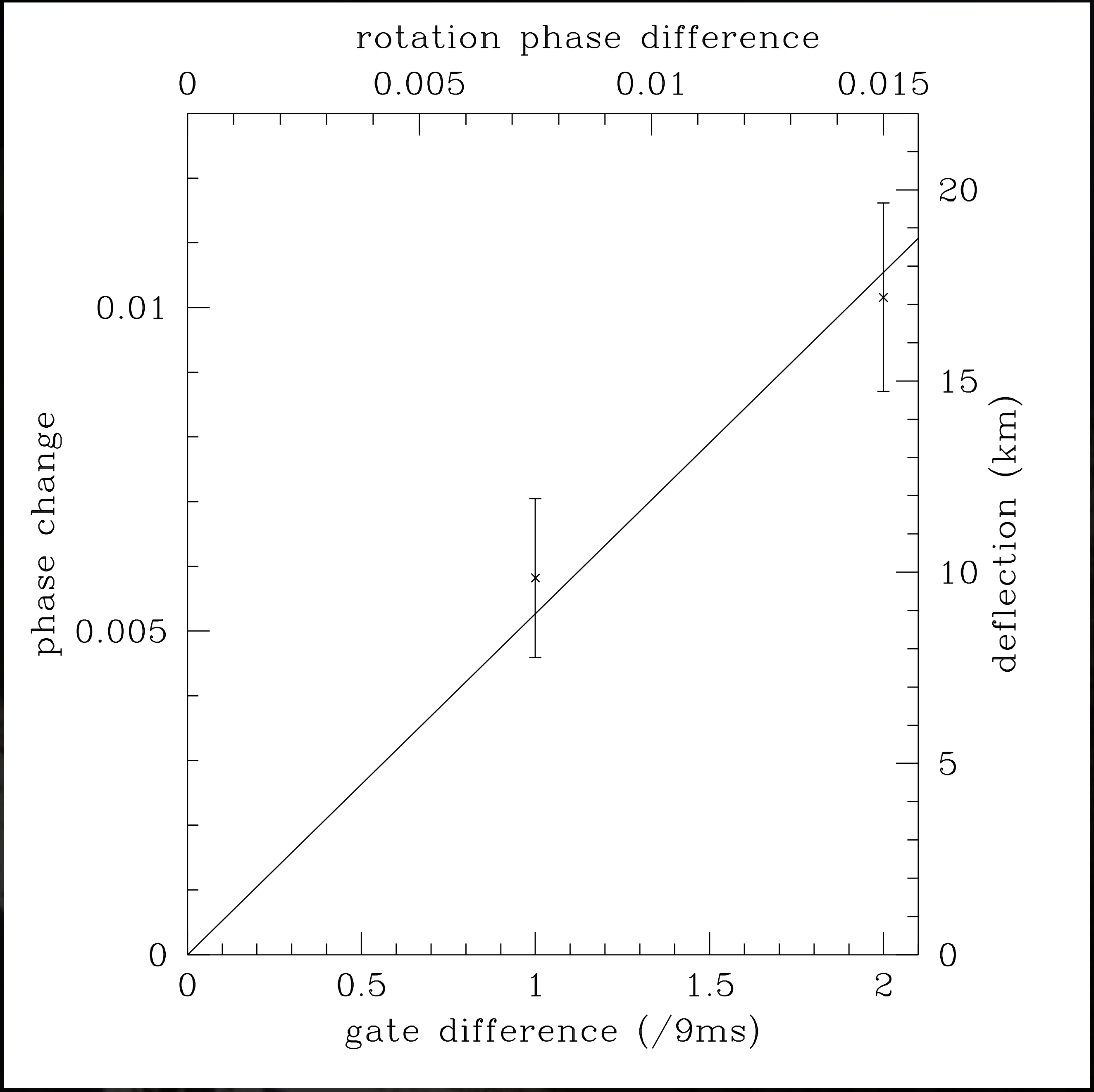






[Pen et al. (2014)]

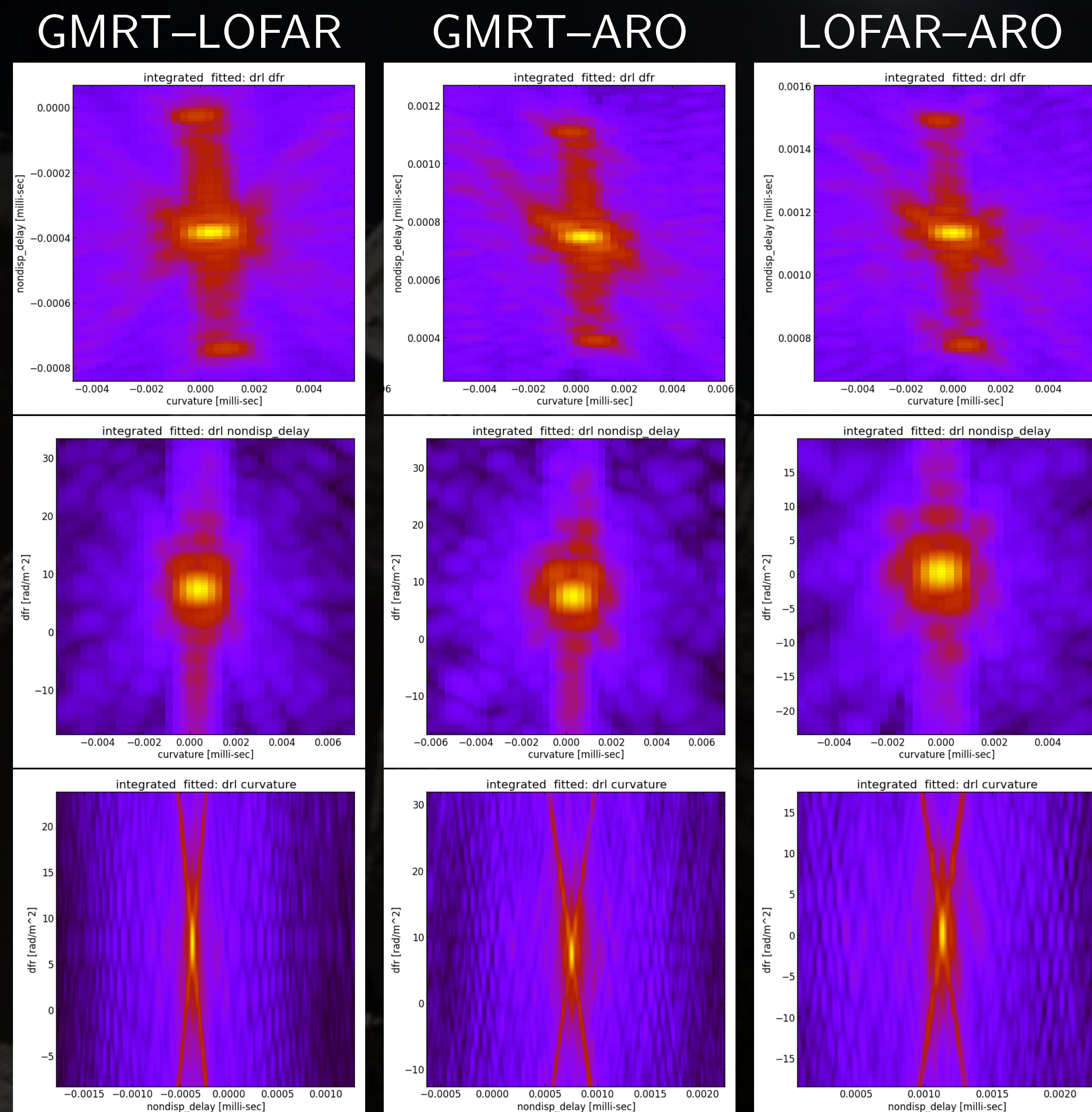
Result for pulsar B0834+06



[*Pen et al. (2014)*]

Ongoing project: LOFAR+KAIRA+GMRT+ARO

- Jul 2013, Jan 2014
- for orbits
- J1012+5307, B1957+20, J1810+1744, . . .
- fringes B1919+21
- VLBI around 150 MHz
- $>$ 10 000 km baseline
- U.-L. Pen, M. v. Kerkwijk, OW, . . .



Summary: Scattering as a tool

- natural interferometers provide extreme resolution
  $\Delta\theta \propto 1/\lambda$ $\leadsto$ low frequencies!

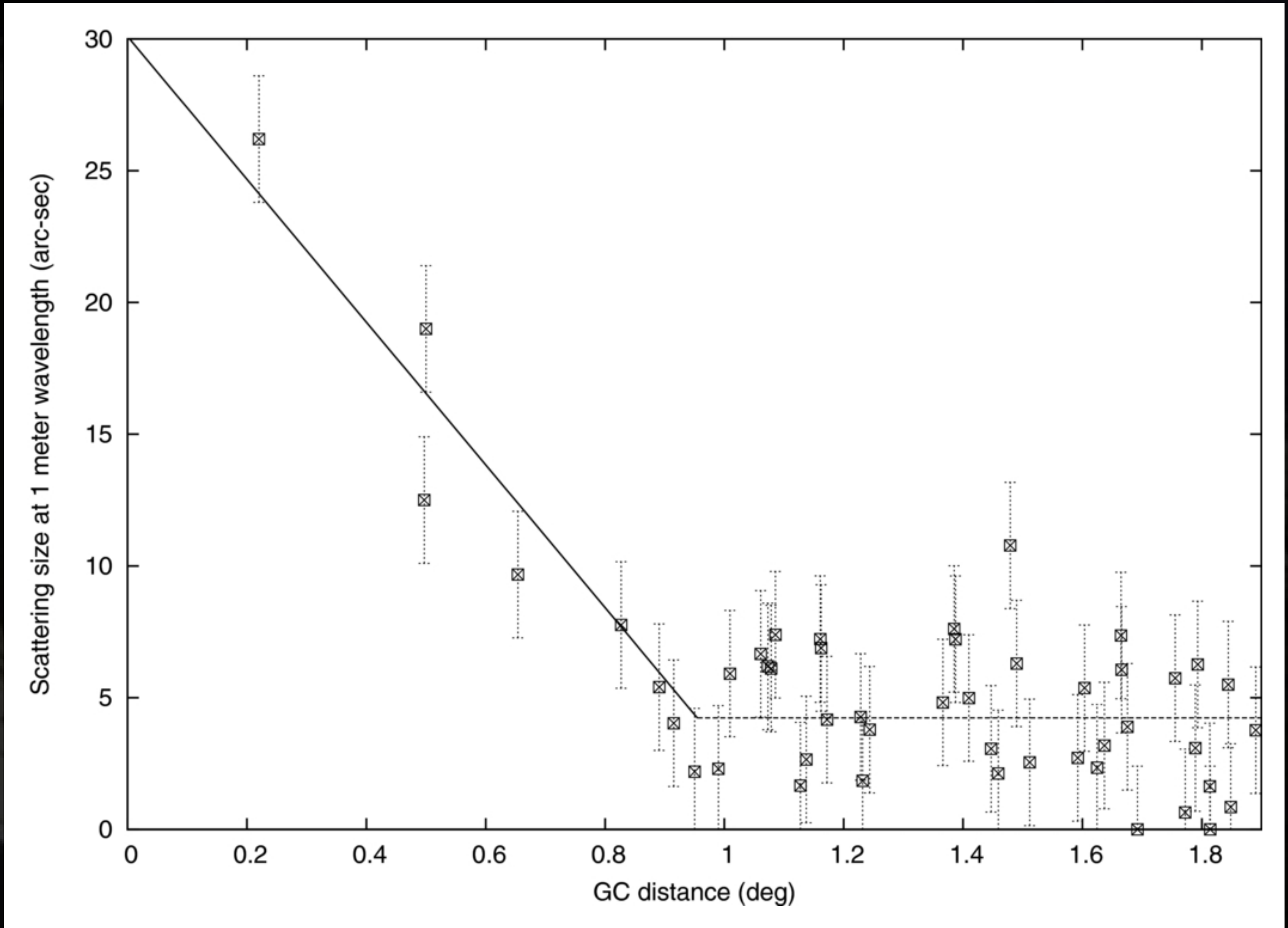
- in almost all cases: too much resolution

- exception: pulsars
  - ⋆ measure motion of emission regions
  - ⋆ maybe resolve emission regions?
  - ⋆ measure proper motion in binary pulsars
  - ⋆ determine orbits, GR tests, etc.

- unfortunately not: Sgr A*
  - ⋆ resolution in L band: $\sim 100\,\mathrm{km}$!
  - ⋆ resolved out even at high frequencies

Bonus: Scattering across GC region

scattering size of extragalactic radio sources at $\lambda = 1\,m$

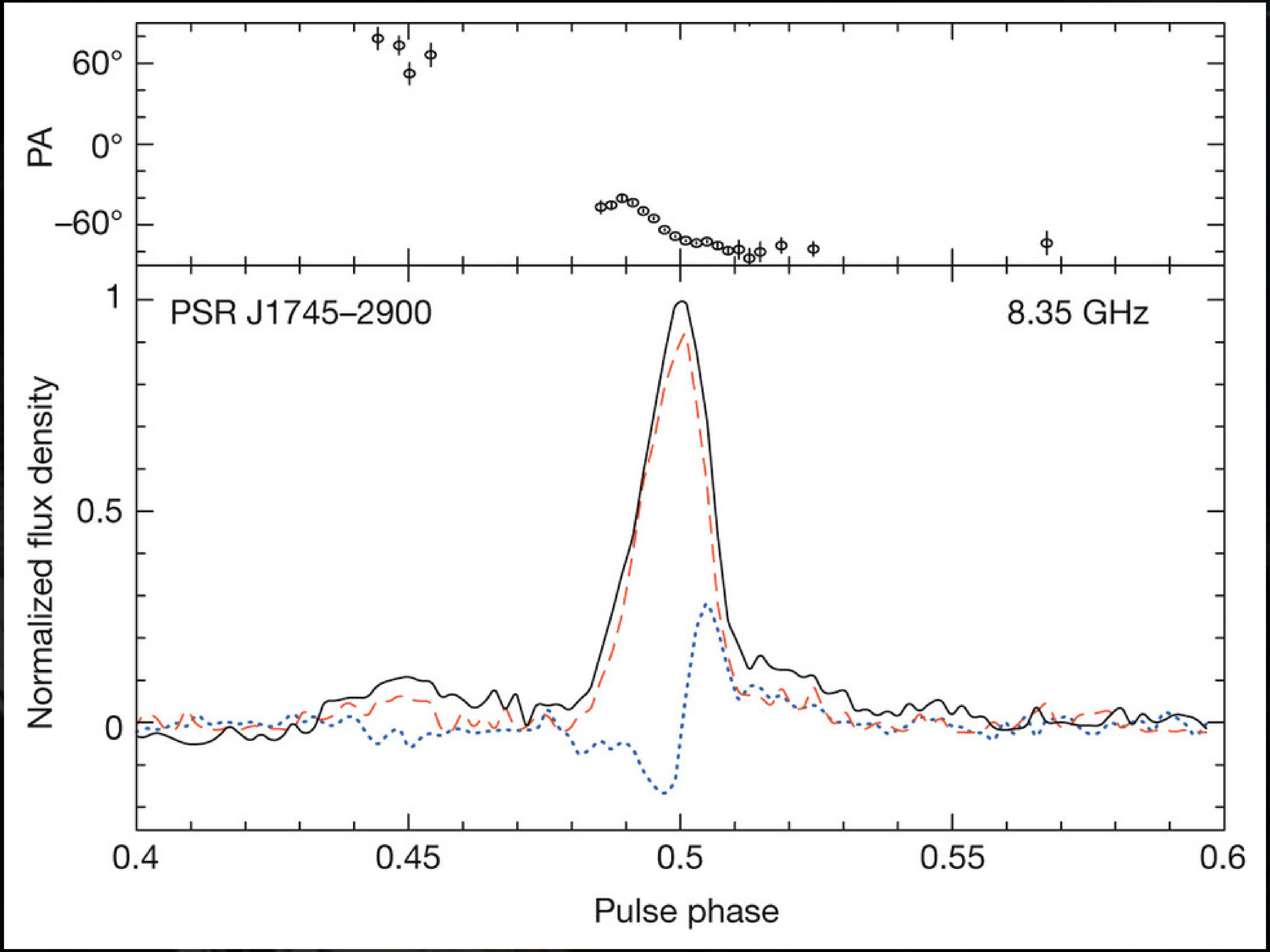


[Roy (2013)]

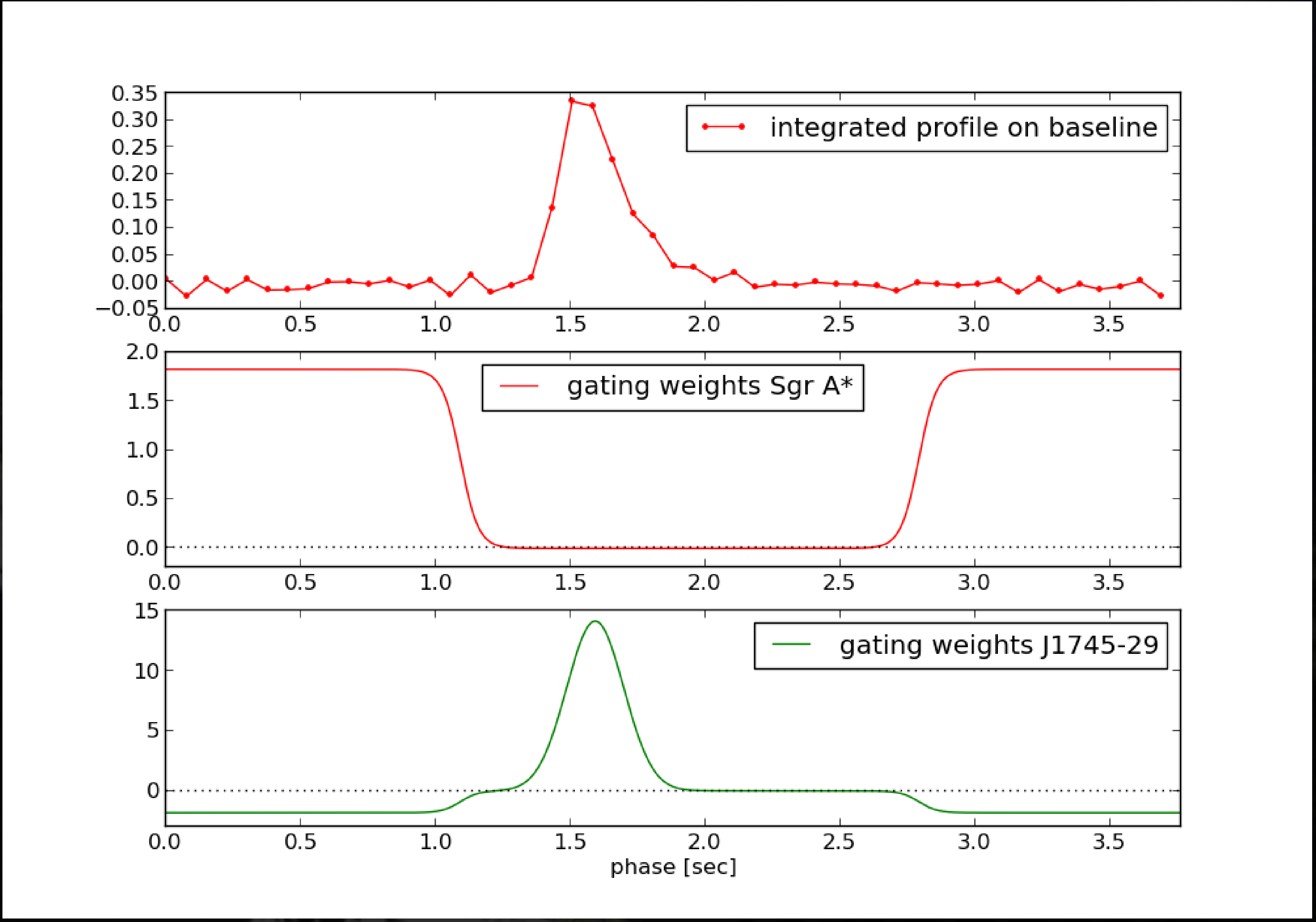
evidence for region of 150 pc around Sgr A*

Bonus: Radio profile of J1745-29

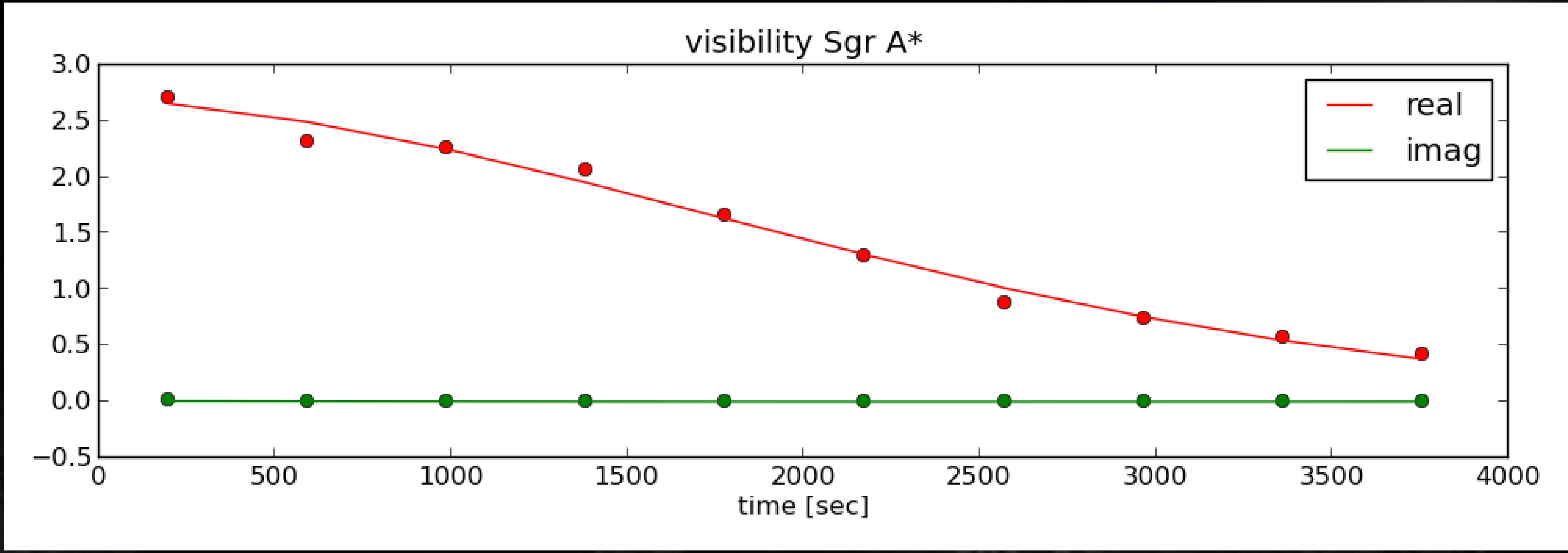
[Eatough et al. (2013)]

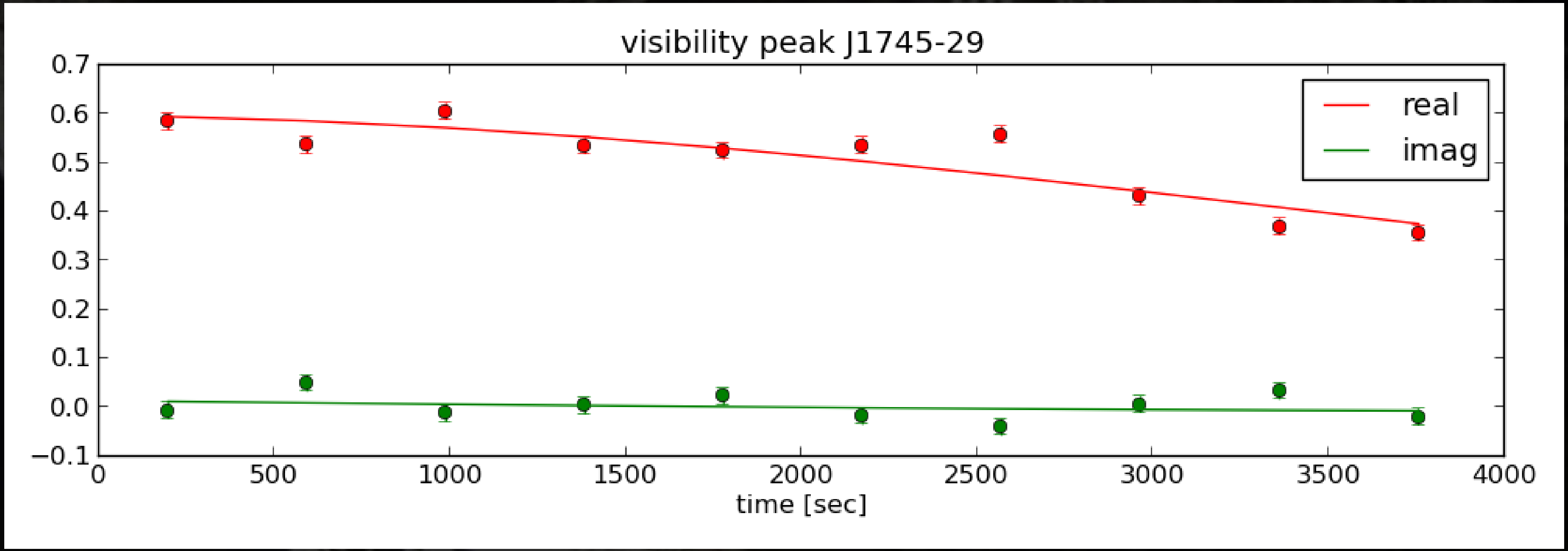


Bonus: Profile and gating functions



Bonus: Visibilities





Bonus: Dirty maps as function of τ