Sgr A*

Two epochs VLBA Imaging of Sgr A* at 86 GHz

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At 30

In collaboration with

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Sgr A*
- as a gravitational source

- dark mass ~ 3 x 10^6 M_{sun} within a radius of 15 mas = 120 AU = 2000 R_{sch}
（motions of *s like S0-2）
- M_{SgrA*} > 4 x 10^5 M_{sun}
（motions of Sgr A* itself）

Sgr A*
- as a radiative source

- X-ray flaring of 200 – 900 sec rise/fall timescales
  => 7 - 30 R_{sch} or 0.05 - 0.2 mas
  （Chandra and XMM-Newton）

- IR flares of 30 – 40 min
  => 5 AU (80 R_{sch}) or 0.6 mas
  （ VLT and Keck）

- Correlated radio/X-ray variation (Zhao et al 04’)
  => $r_{Radio} > r_{X\text{-}ray} = 7\ R_{sch}$ or 0.05 mas

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VLBI Observations of Sgr A*

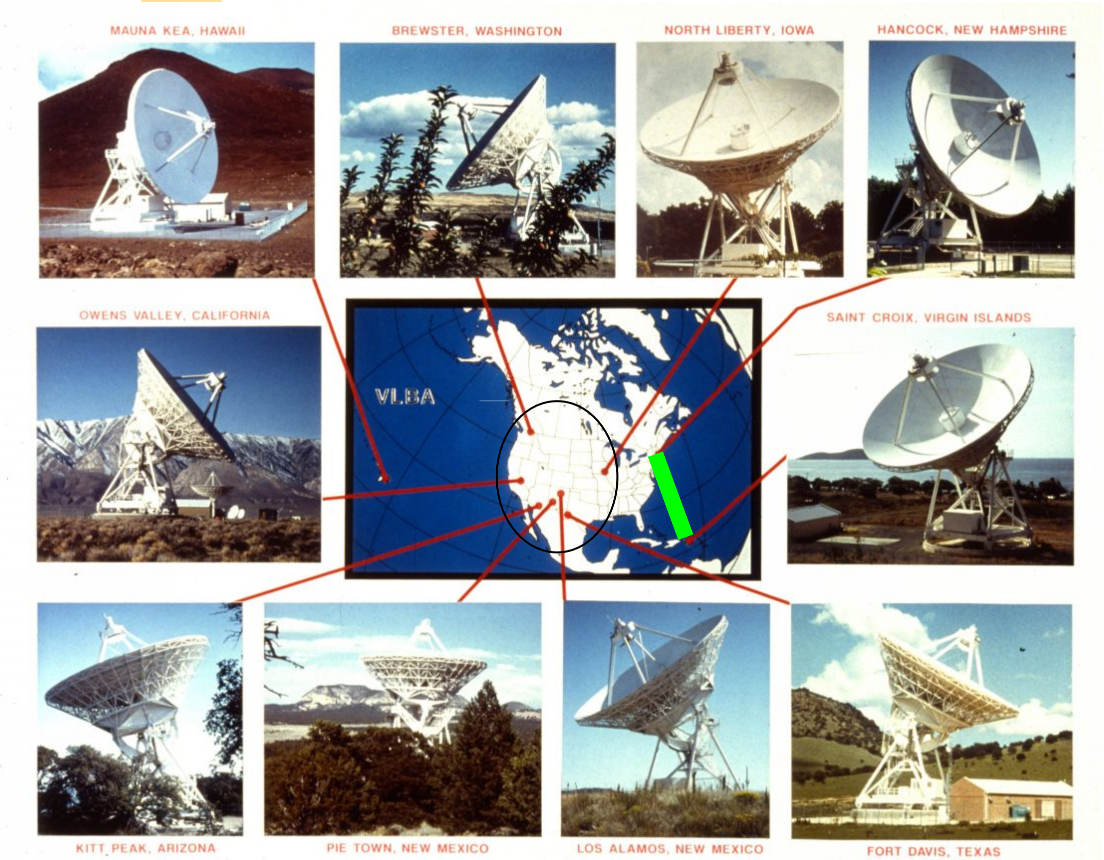
- Interstellar scattering effect dominates the cm-VLBI images of SgrA* by λ^2– law, with an *apparent* E-W elongated shape

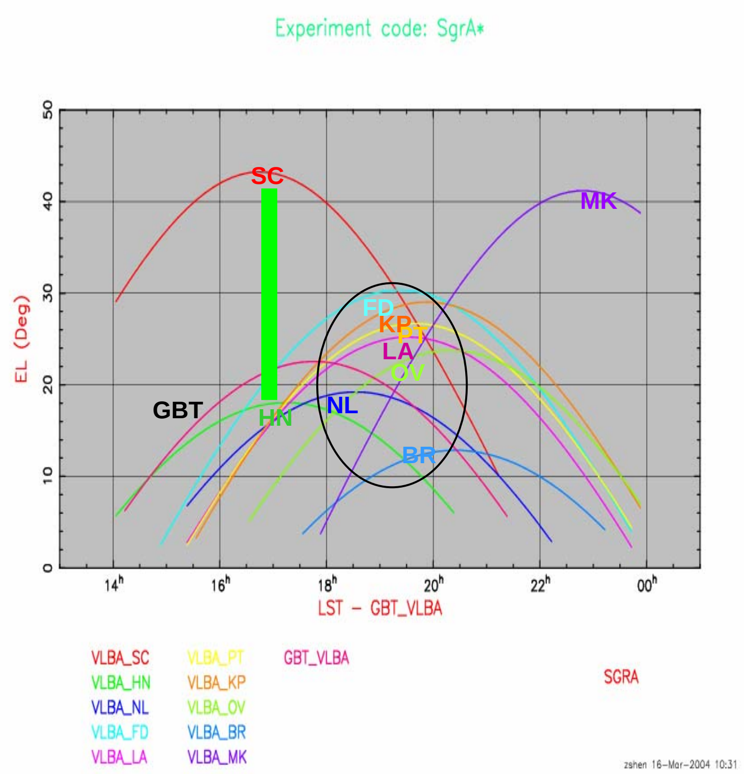
- need for the mm-VLBI

Mm-VLBI Observations of Sgr A*

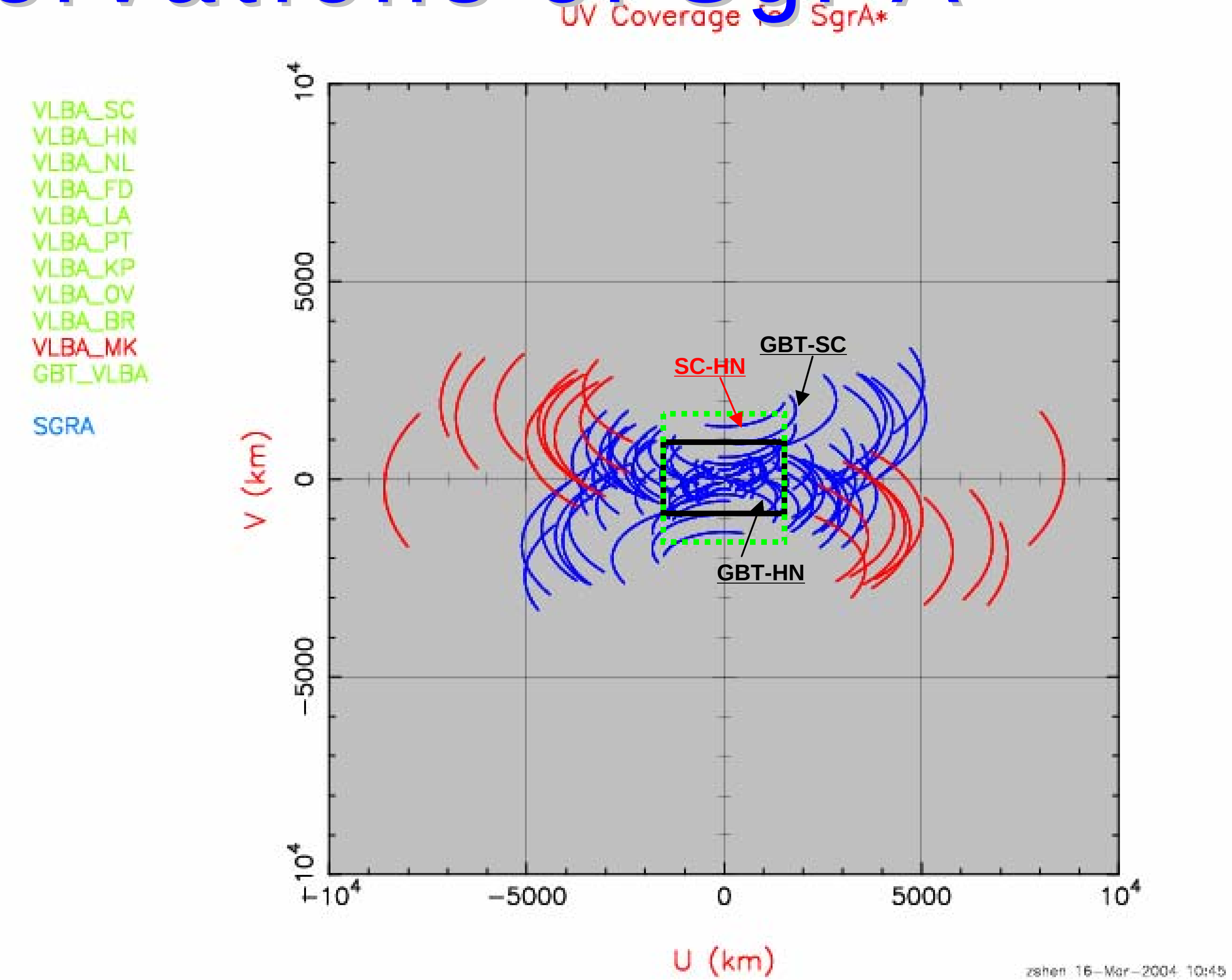
- The mm-VLBI plagued by 2 facts
  - southerly Dec of SgrA* (~ - 30^{o})
  - northern lat. for most mm-VLBI antennas

Uptime plot of VLBA Observations of Sgr A*





(u,v) coverage of VLBA Observations of Sgr A*



Mm-VLBI Observations of Sgr A*

- The mm-VLBI plagued by 2 facts
- southerly Dec of SgrA* (~ - 30^{o})
- northern lat. for most mm-VLBI antennas

- lack of spatial resolution in N-S (= minor axis)
- severe atmospheric effects on data calibration

(large and variable opacity, short and variable T_{coh})

+ compromised sensitivity at mm-band

(high Tsys: >100 K at zenith; low antenna efficiency: < 45%)

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How to improve

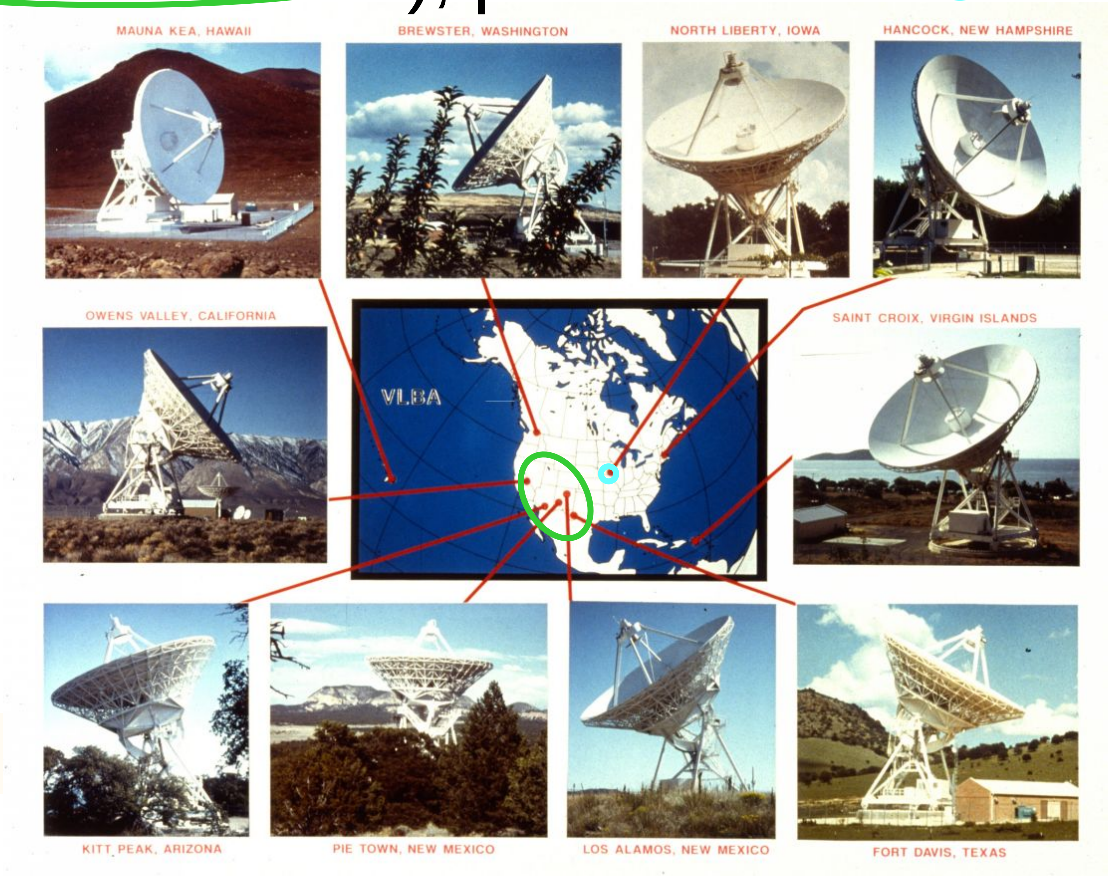
- During the observations
  - ☑ dynamic scheduling -> best weather condition
  - ☑ compact SiO masers for amp cal and pointing
- During the data analysis
  - ☑ closure amplitudes to constrain the model-fitting

1st epoch 3mm VLBA Observation

- Nov 3, 2002 (dynamic since Feb 2001)
- 512 Mbps (highest recording rate)
- Frequent pointing check (every 15 min)
- Very good detections among 5 antennas (FD/KP/LA/OV/PT), plus some to NL
- First 3mm VLBI image of SgrA*

1st epoch 3mm VLBA Observation

- Very good detections among 5 antennas (FD/KP/LA/OV/PT), plus some to NL



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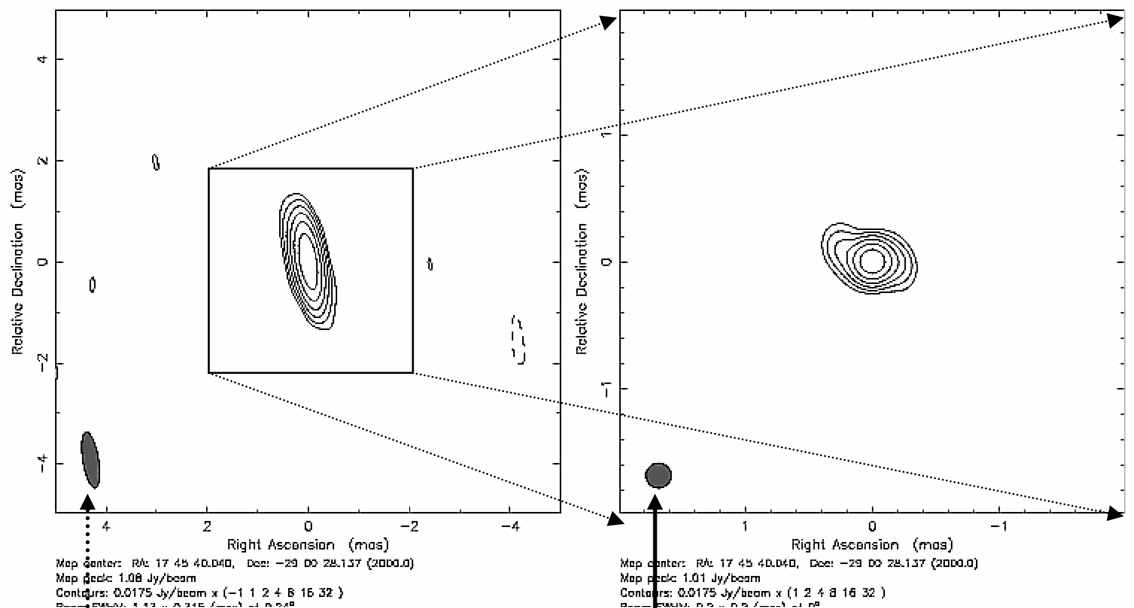
1st epoch 3mm Observation

- **First 3mm VLBI image of SgrA***



UN beam 1.11 mas x 0.32 mas @ 9^o

Super-resolution 0.02 mas

- unresolved (no extended structure) → single component
- zero closure phases
- ~ E-W elongated emission → consistent with λ ⩾ 7mm data

Model-fitting using the closure amplitude constraints

- χ^2 – *minimization* algorithm

$$\chi^2 = \sum_t \sum_{ij} w_{ij} \,|\, A_{ij}^{obs}(t) - G_i(t) G_j(t) A_{ij}^{\mathrm{mod}}(t) \,|^2$$

here, the visibility amplitude A_{ij} is used,

"good observable" - the closure amplitude

$$C_{ijkl} = \frac{A_{ij} A_{kl}}{A_{ik} A_{jl}}$$

is conserved by assuming an antenna-dependent gain G_i only.

This is equivalent to the use of closure quantities!

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Bias Correction

- The measured visibility amplitude <Z> has a positive bias with respect to the true amplitude A

$$< Z > \approx A\left(1 + \frac{\sigma^2}{2A^2}\right) \qquad (strong\ signal: A >> \sigma)$$

$$< Z > \approx \sigma\sqrt{\frac{\pi}{2}}\left(1 + \frac{A^2}{4\sigma^2}\right) \qquad (weak\ signal: A << \sigma)$$

here, σ is the rms deviation of a single component of the complex noise vector. This is big at low SNR $\leqslant$ 3, but can be corrected (see Thompson, Moran, & Swenson 1986)

However, it is difficult to estimate the unbiased $\mathbf{C}_{ijkl}$ and thus to treat its formal error properly if we fit the closure amplitude directly (see Trotter, Moran, & Rodriguez 1998).

Model-fitting procedure

- χ^2 – *minimization* algorithm

- Bias correction to the measured visibility amplitude $A_{ij}(t)$
- Determination of the antenna-based gain $\mathcal{G}_i$ from the observed visibility amplitude A and the given model $\tilde{A}$ at each time t
- Comparison of χ^2 for different model $\tilde{A}$ to get the best fit model
- Error estimate from the χ^2 distribution

  1 σ (68.3% confidence): $\chi^2(\mathrm{min}) \to \chi^2(\mathrm{min}) + \underline{\chi^2(\mathrm{min}) / N_{dof}}$

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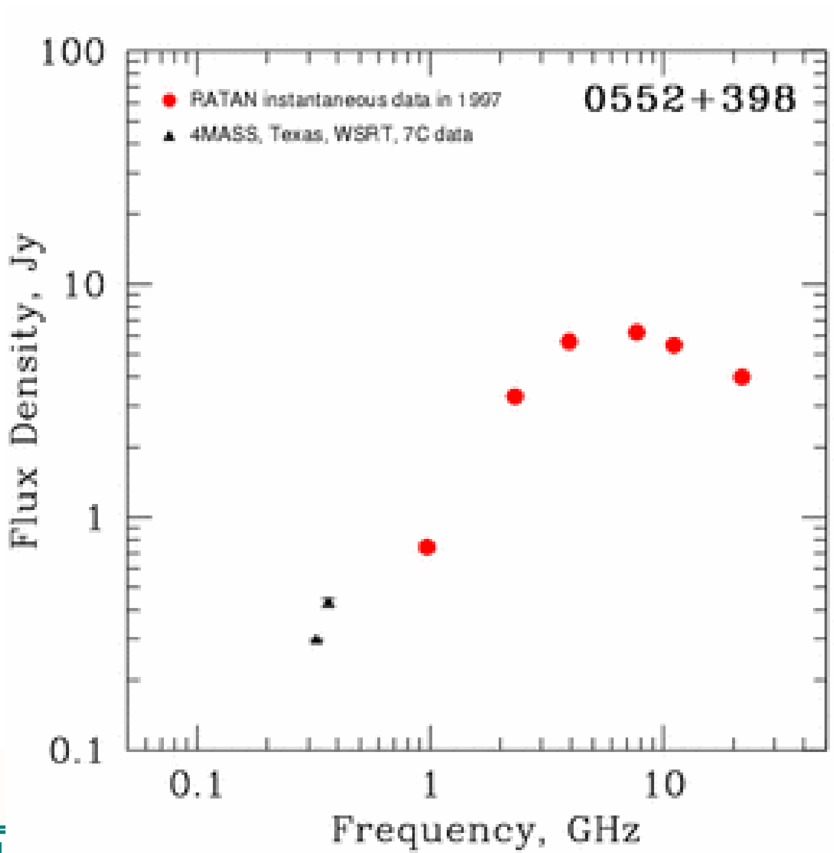
Application to DA193

- DA193 (z=2.365)



GPS source

VLBI calibrator

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Sgr A*

Application to DA193

- **DA193: VLBI calibrator**

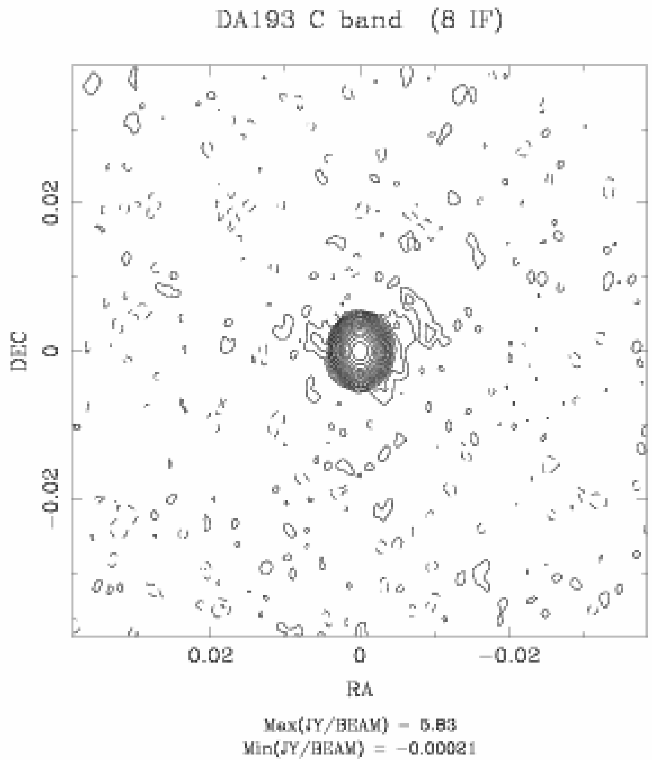

Figure 9.13: High dynamic range image of DA193. Peak to off-source RMS is 115,000:1

D. Briggs thesis (1995)

DR = 115,000:1

fit with a single Gaussian

0.904 x 0.514 mas @109.5^{o}

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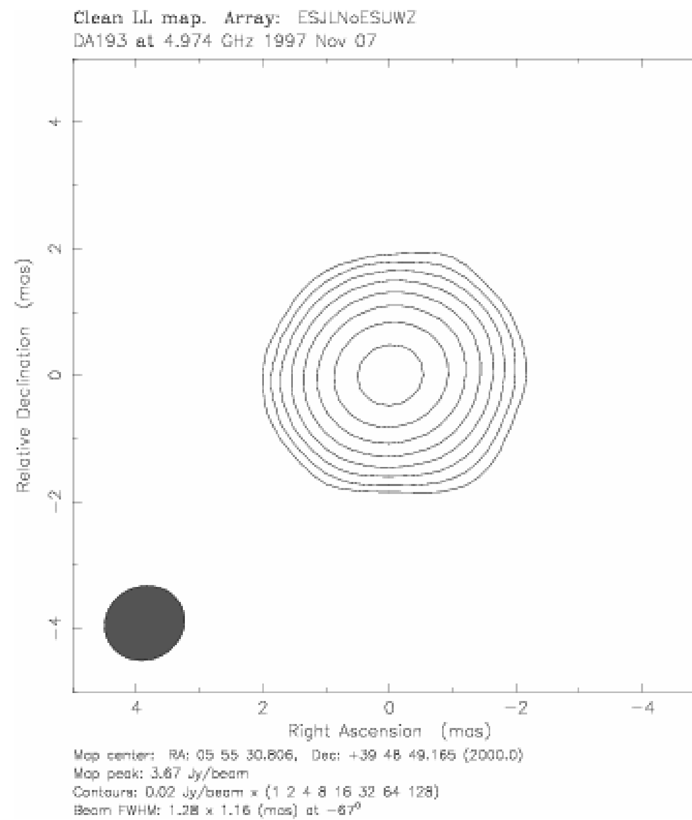
Application to DA193

- DA193: EVN+Sh+Ur+Hart (Nov 7, 1997)
- Standard VLBI self-calibration imaging and model-fitting

  0.82 x 0.64 mas @ 111^{o}

- Our procedure

  0.82 x 0.48 mas @ 108^{o}



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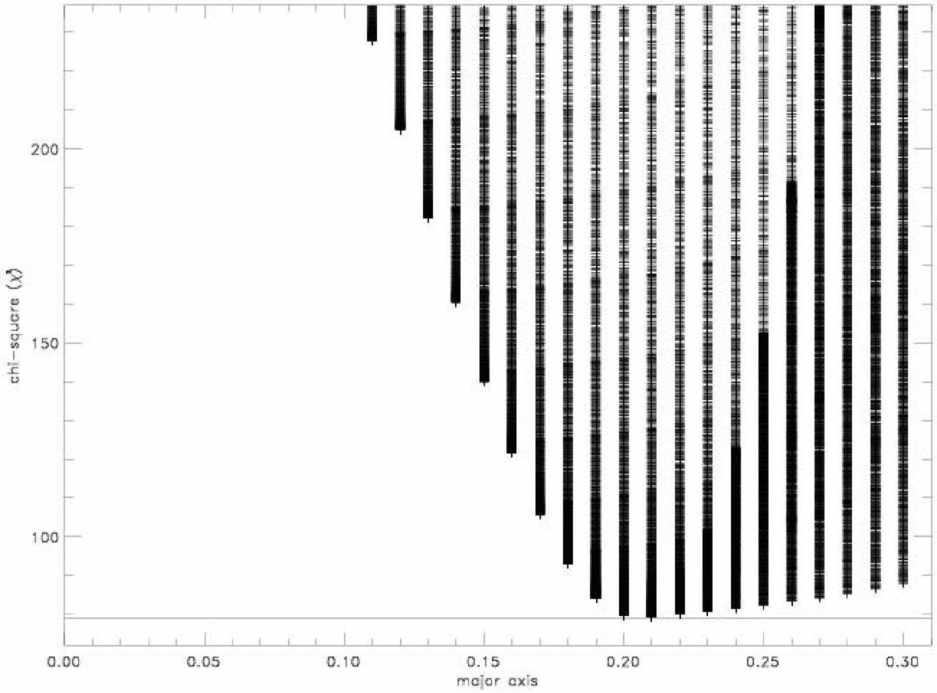
1st epoch 3mm Observation

- **major axis: 0.21 (+0.02 / -0.01) mas**



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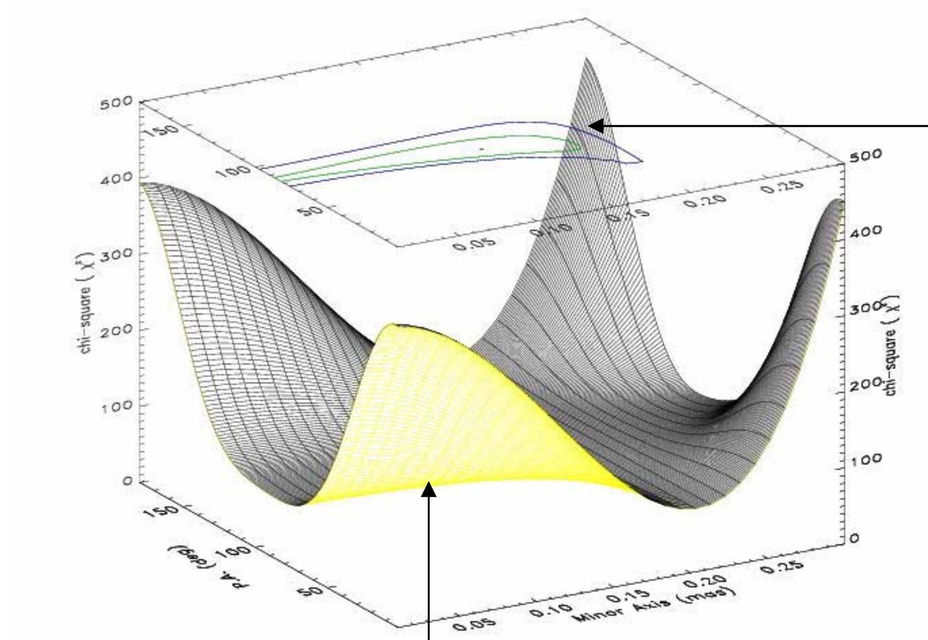
1st epoch 3mm Observation

- Minor axis: 0.13 (+0.05 / -0.13) mas and PA: 79° (+12° / -33°)



Contour plot showing the Confidence intervals of 68.3% and 90.0%.

Surface plot of Chi^2 as a function of both minor axis and PA (major axis = 0.21 mas).

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Sgr A*

1st epoch 3mm Observation

- **Model fitting:**

✓ **Single elliptical Gaussian**

major axis: 0.21 (+0.02 / -0.01) mas

minor axis: 0.13 (+0.05 / -0.13) mas

position angle: 79^o ($+12^o$ / -33^o)

✓ **Best Circular Gaussian**

FWHM: 0.20-0.21 mas

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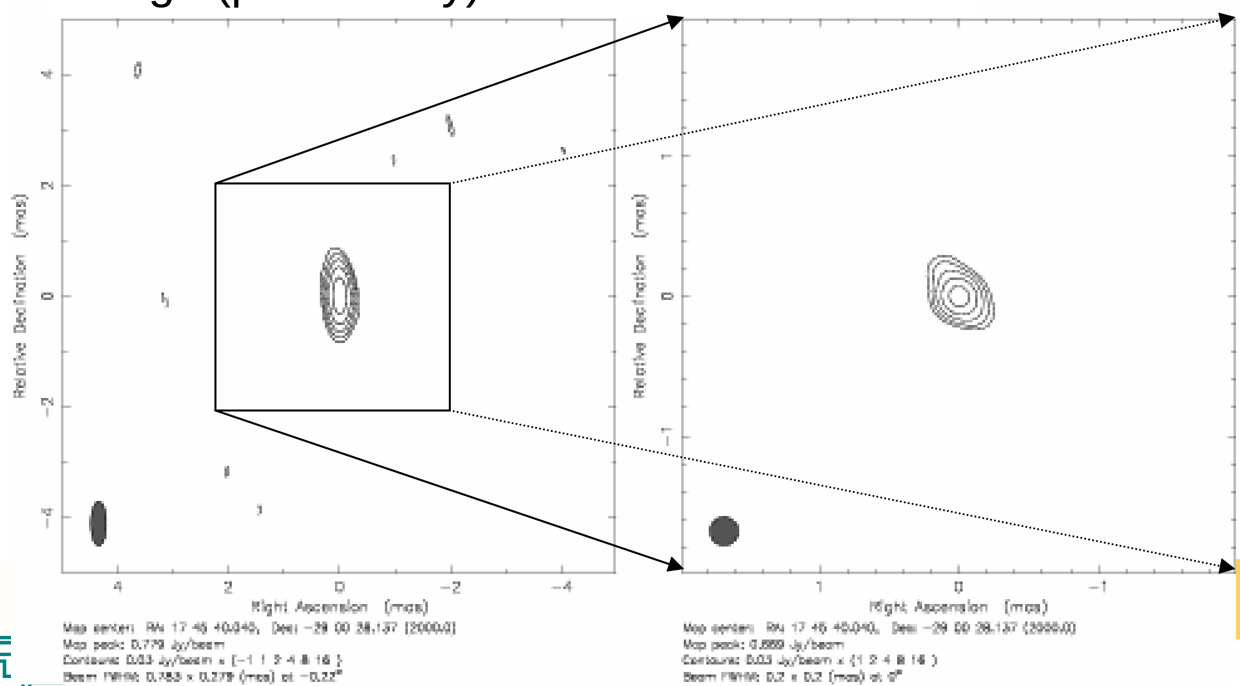
2nd epoch 3mm VLBA Observation

- Observations on Sept 28, 2003
  - ✓ 512 Mbps; pointing check every 15 min
  - ✗ gust @OV, tape (recording,playback)@KP, PT

Image (preliminary)



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Sgr A*

2nd epoch 3mm Observation

- **Model fitting:**

✓ **Single elliptical Gaussian**

major axis: 0.21 (+0.01 / -0.01) mas

minor axis: 0.00 - 0.13 mas

position angle: 87^o (+12^o / -9^o)

✓ **Best Circular Gaussian**

FWHM: 0.20 mas

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Discussion

- *Apparent* SgrA* structure at 3mm: elongated roughly along E-W with a major axis size of 0.21 mas

	Elliptical Gaussian Model (major,minor,pa)	circular
1999 Apr, CMVA (Doeleman et al 2001)	0.34(+/-0.14), 0.17(+/-0.02), 22(+/-20)	0.18(+/-0.02)
2002 Nov, VLBA	0.21(+0.02/-0.01), 0.13(+0.05/-0.13), 79(+13/-33)	0.20 - 0.21
2003 Sept, VLBA	0.21(+0.01/-0.01), 0.00-0.13, 87(+12/-9)	0.20

Discussion

- *Intrinsic* structure of SgrA* emission

The best ever measurement in Nov 2002 shows a 3 σ deviation from the extrapolated scattering angle of 0.175 +/- 0.003 mas along the major axis. If confirmed, this indicates an intrinsic size of 0.116 mas, or ~1 AU @ 8 kpc, or ~17 Rsch (3 x 10^6 M_{sun}).

Intrinsic Tb ~ 1.5 x 10^{10} K (non-thermal origin)

Sgr A*

Discussion – 7mm data

Epoch	Ctr Freq(+BW) GHz (+ MHz)	S (Jy)	Major axis (mas)	Minor axis (mas)	P.A (degree)	Reduced chi^2	SC-HN	Notes
1994.32	43.151 (64)	1.4	0.72 +/- 0.01	0.39 +/- 0.07	78 +/- 2	1.11	yes	
1994.75	43.151 (64)	1.3	0.72 +/- 0.01	0.42 +/- 0.03	79 +/- 1	1.17	yes	Bower & Backer 1998
1997.12	43.213 (32)	1.0	0.71 +/- 0.01	0.42 +/- 0.05	74 +/- 2	2.89	no	Lo et al 1998; dual pol
1999.31	43.135 (32)	1.0	0.69 +/- 0.01	0.33 +/- 0.04	83 +/- 1	0.97	yes	1.26 x 0.44 @ 7º
1999.39	43.135 (32)	1.5	0.71 +/- 0.01	0.44 +/- 0.02	79 +/- 1	1.59	yes	1.35 x 0.48 @ 11º
1999.41	43.135 (32)	1.5	0.75 +/- 0.01	0.49+/- 0.05	70 +/- 3	0.85		
	39.135 (32)	1.6	0.86 +/- 0.01	0.54+/- 0.03	78 +/- 1	1.54		39 GHz
	45.135 (32)	1.5	0.66 +/- 0.01	0.42 +/- 0.04	75 +/- 3	1.31		45 GHz
2001.58	42.8-43.1 (32)	0.9	0.74 +/- 0.01	0.47 +/- 0.14	77 +/- 6	3.41	yes	

Average over 7 epochs: major 0.72 +/- 0.02 mas
minor 0.42 +/- 0.04 mas
P.A. 77 +/- 3 deg

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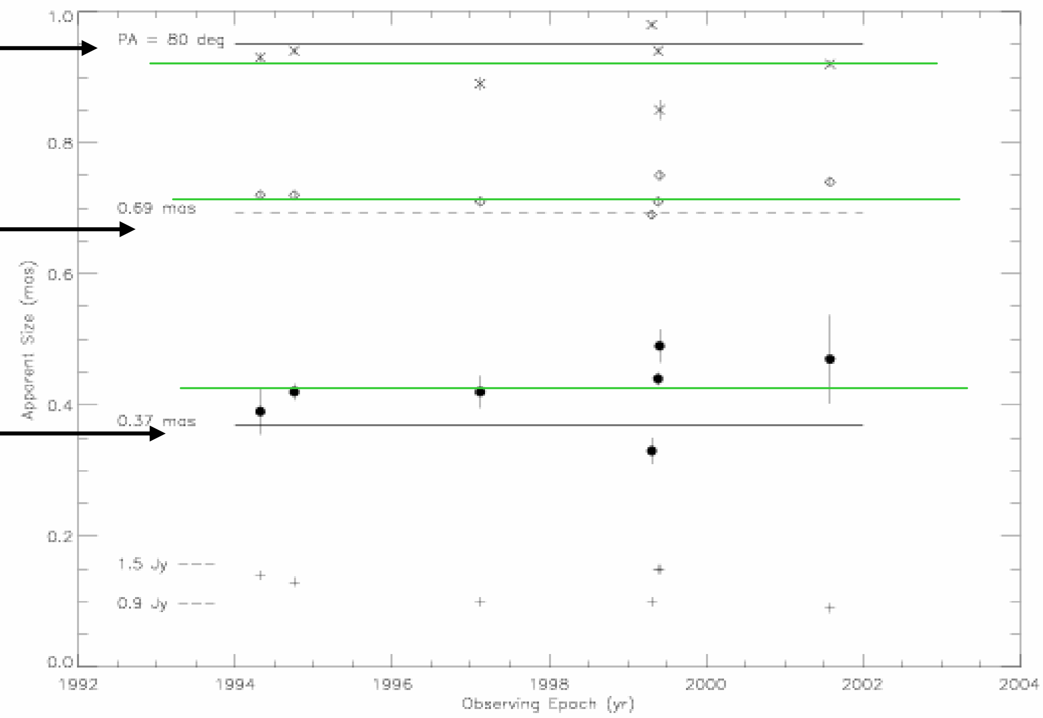
Discussion – 7mm data

P.A.

Major axis

Minor axis



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Discussion – past SgrA* size measurements

Table 1. Summary of published Sgr A* size measurements

Epoch (yrs)	S_{VLBI} (Jy)	θ_{major} (mas)	θ_{minor} (mas)	Axial Ratio ($\theta_{minor}/\theta_{major}$)	P.A. (°)	References
			$\lambda = 35.6$ mm			
1997.10	0.73±0.10	18.0±1.53	9.88±1.68	0.55±0.14	78±6	Lo *et al.* (1998)
1991.90		17.5±0.5	8.5±1.0	0.49±0.06	87±5	Lo *et al.* (1993)
1983.36		16.1±0.3	16.1	1.0		Marcaide *et al.* (1992)
1983.35		15.5±0.1		0.55±0.25	98±15	Lo *et al.* (1985)
1982.30		17.4±0.5		0.53±0.10	82±6	Jauncey *et al.* (1989)
1978.07	0.7	18±2	18	1.0		Lo *et al.* (1981)
1976.18	0.9±0.06	14±2	14	1.0		Lo *et al.* (1977)
1975.38	0.6±0.1	<20.0		1.0		Lo *et al.* (1975)
1974.50		17.0	17.0	1.0		
			$\lambda = 13.5$ mm			
1997.10	0.74±0.04	2.70±0.15	1.50±0.59	0.56±0.25	81±11	Lo *et al.* (1998)
1992.85	1.05±0.10	2.67±0.15	1.63±0.41	0.61±0.12	79±10	Marcaide *et al.* (1999)
1991.49	0.98±0.05	2.6±0.2	1.3	0.5	87	Lo *et al.* (1993)
1991.47	1.07±0.15	2.60±0.20	1.30±0.88	0.5±0.3	80±15	Alberdi *et al.* (1993)
1985.11	1.2±0.4	1.8±0.09	1.8	1.0		Marcaide *et al.* (1992)
1983.47	0.98±0.05	2.2±0.2	1.21±1.21	0.55±0.5	87±30	Lo *et al.* (1985)
			$\lambda = 6.9$ mm			
1997.10	1.03±0.01	0.70±0.01	0.58±0.07	0.83±0.11	87±8	Lo *et al.* (1998)
1994.75	1.28±0.10	0.76±0.04	0.55±0.11	0.73±0.10	77±7	Bower & Backer (1998)
1992.62	2.10±0.10	0.74±0.03	0.40±0.20	0.54±0.29	90±10	Backer *et al.* (1993)
1992.40	1.42±0.10	0.75±0.08	0.75	1.0		Krichbaum *et al.* (1993)
			$\lambda = 3.5$ mm			
1999.27	1.4	0.34±0.14	0.17±0.02	0.50±0.26	22±20	Doeleman *et al.* (2001)
	1.4	0.18±0.02	0.18	1.0		Doeleman *et al.* (2001)
1995.18	1.80±0.30	0.19±0.03	0.19	1.0		Krichbaum *et al.* (1998)
1994.25	1.40±0.20	0.15±0.05	0.15	1.0		Rogers *et al.* (1994)
1993.27	1.25±0.35	0.22±0.19	0.22	1.0		Krichbaum *et al.* (1999)

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Discussion – reanalysis of the archived VLBI data

λ (cm)	major (mas)	minor (mas)	p.a. (deg)	Resolution (mas x mas @ deg)	Notes
6.03	43.0 +2.5 /-1.0			21 x 12 @ 4	Only 1 epoch data!
3.56	17.5 +0.5/-1.0	8.50 +/- 1.0	87 +/- 3	12.5 x 6.5 @ 5	
1.96	5.33 +/- 0.07	2.70 +0.30/-0.44	83 +/- 3	9.5 x 3.9 @ 26	1 epoch only!
1.35	2.53 +0.06/-0.05	1.45 +0.23/-0.38	83 +4/-5	6.4 x 2.3 @ 24	
0.69	0.72 +/- 0.02	0.42 +/- 0.04	77 +/- 3	1.6 x 0.5 @ 10	Errors from the scatter of 7 epochs data
0.35	0.21 +0.02/-0.01		79 +12/-33	1.1 x 0.3 @ 9	Minor axis poor

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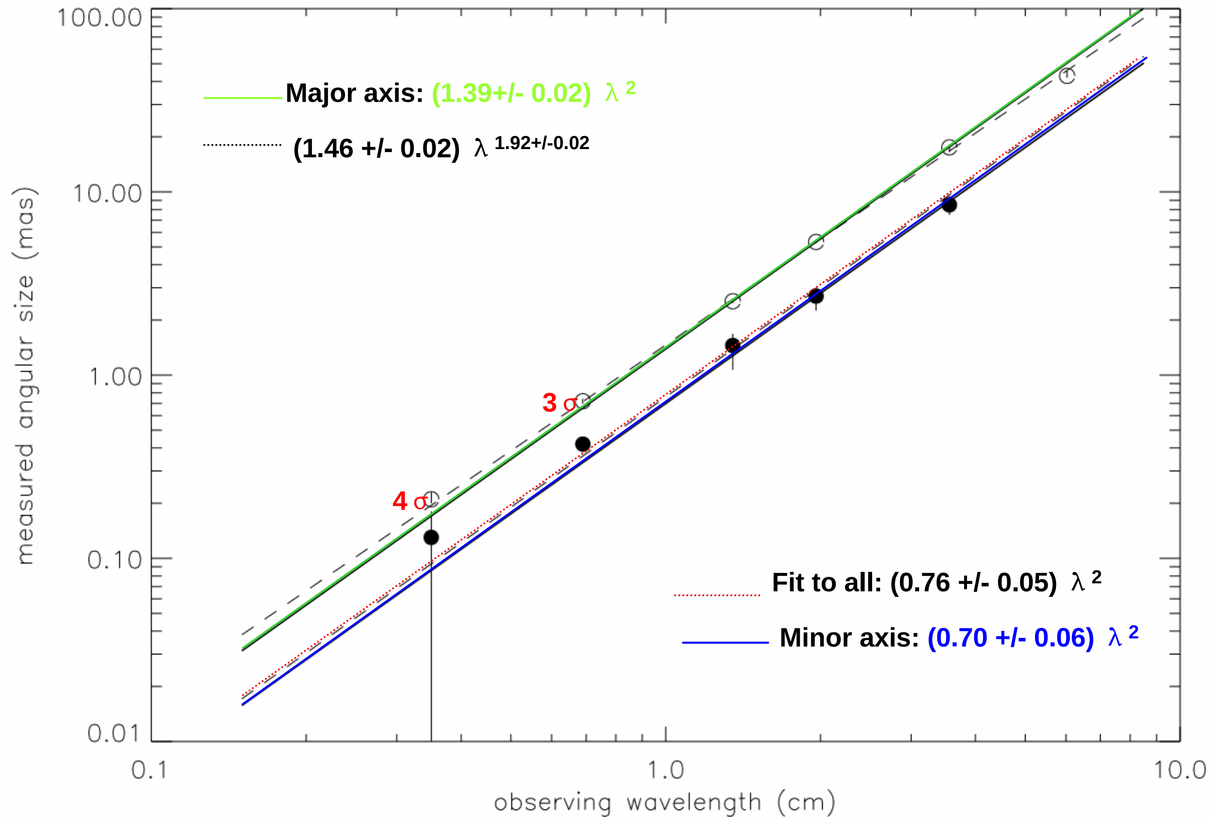
Sgr A*

Scattering law revisited



Summary

- First 3mm VLBA image of Sgr A* shows an E-W elongated structure, consistent with the morphology observed at other longer λ.

- A 3 σ deviation from the extrapolated scattering angle of 0.175 mas at 3mm (from the current 1.43 λ^2) may suggest an intrinsic size of 1 AU along E-W at 3mm.

- Investigation of the archived multi-wavelength data suggests a slightly smaller scattering effect of 1.39 λ^2.

- The current scattering law needs to be re-examined with more measurements at both short (mm) and long (cm) wavelengths.