Galactic Center Black Holes - WG3

COST Action MP0905

Black Holes in a violent Universe

2 4 – 25 June, MPIfR, Bonn, Germany

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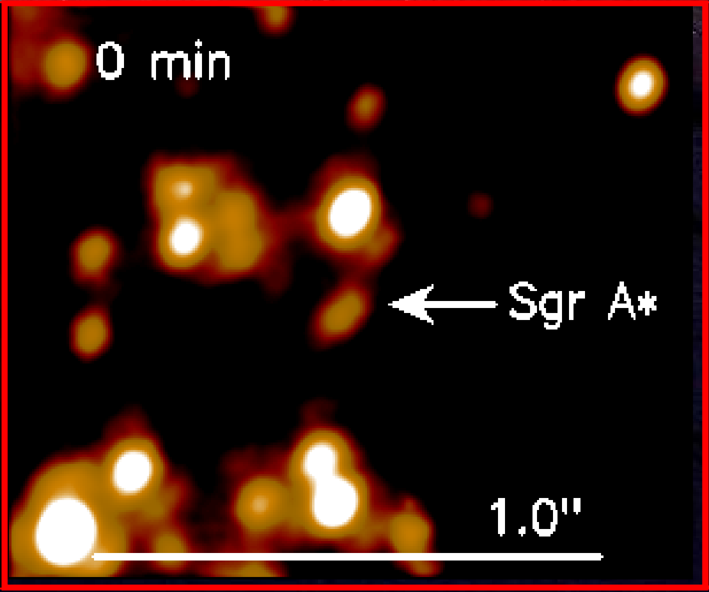
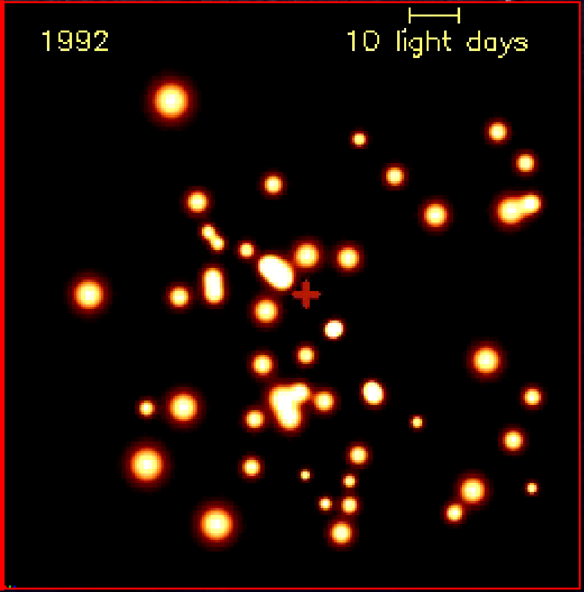
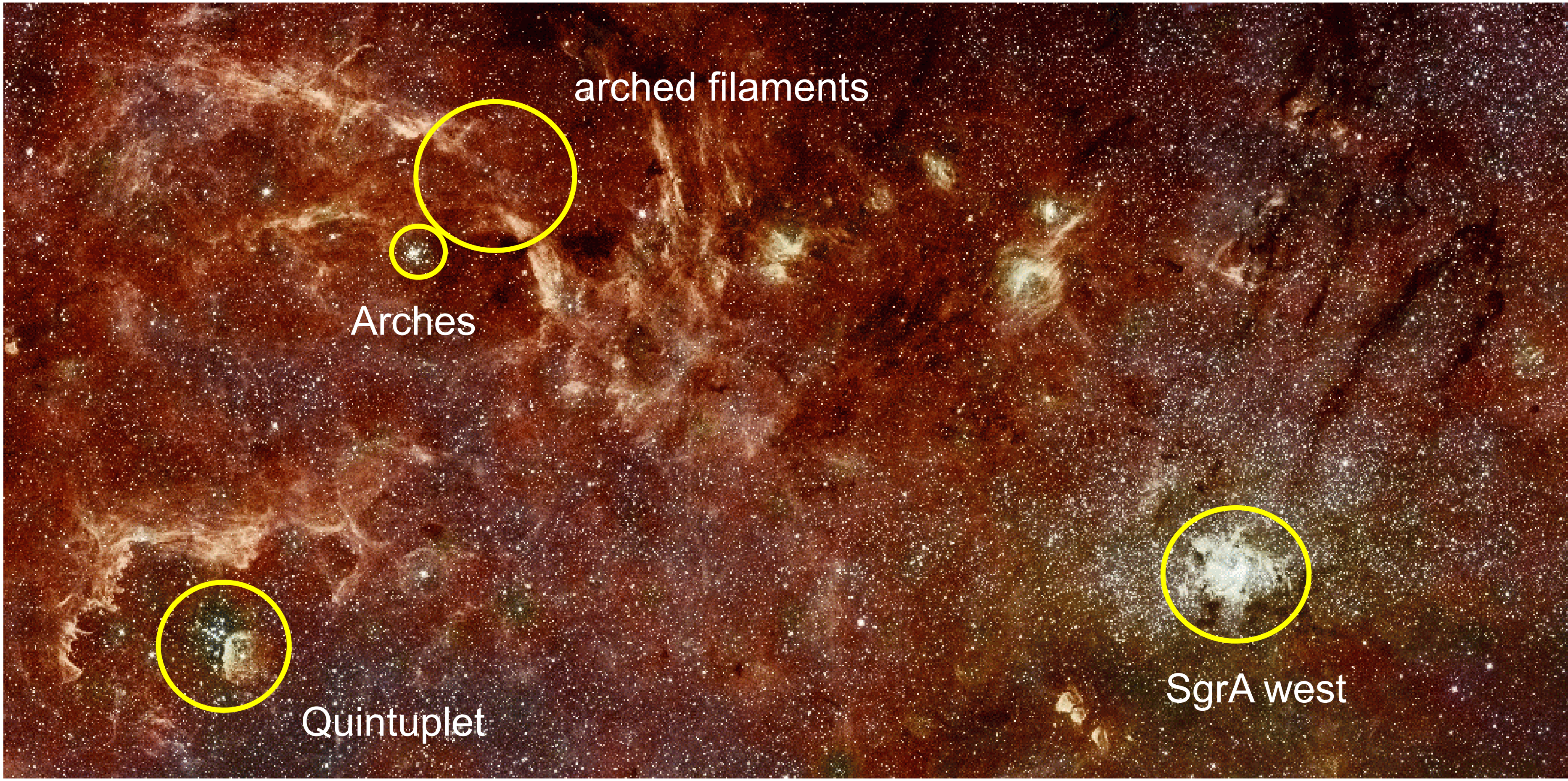




The Galactic Center as seen by SPITZER and HUBBLE

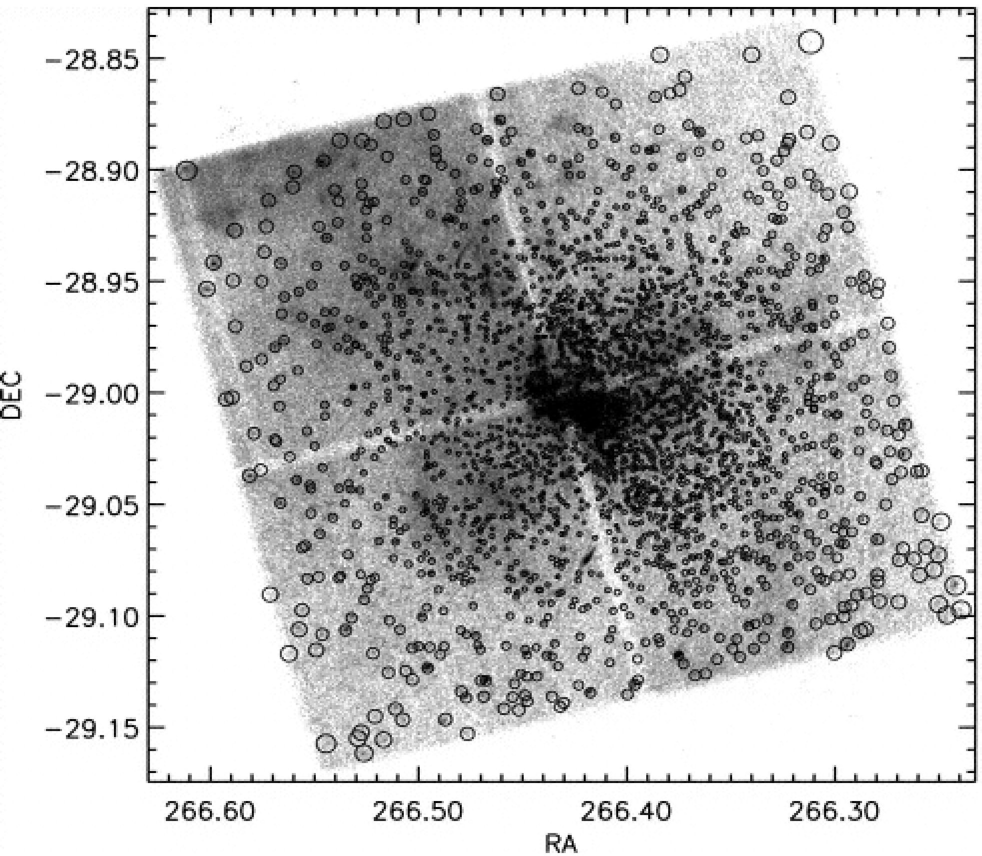


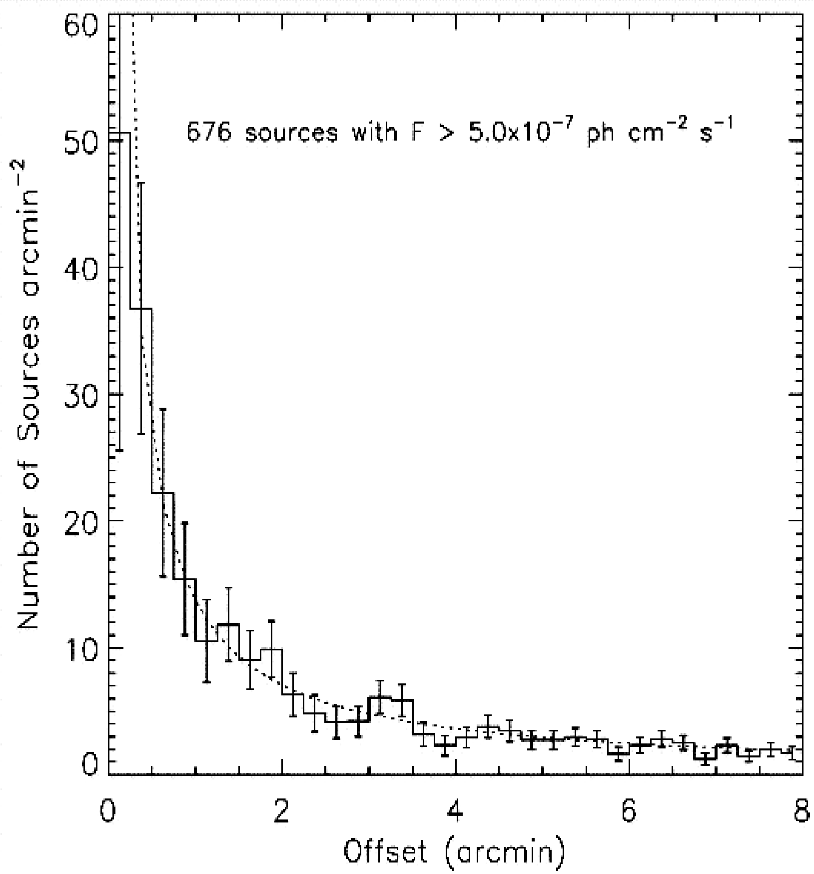
300 x 115 light years = 91 x 34.8 parsec = 38.3 x 14.7 arcmin

NASA ESA D. Q. Wang U. Mass, Amherst NASA JPL SSC/Caltech

Chandra X-ray point sources

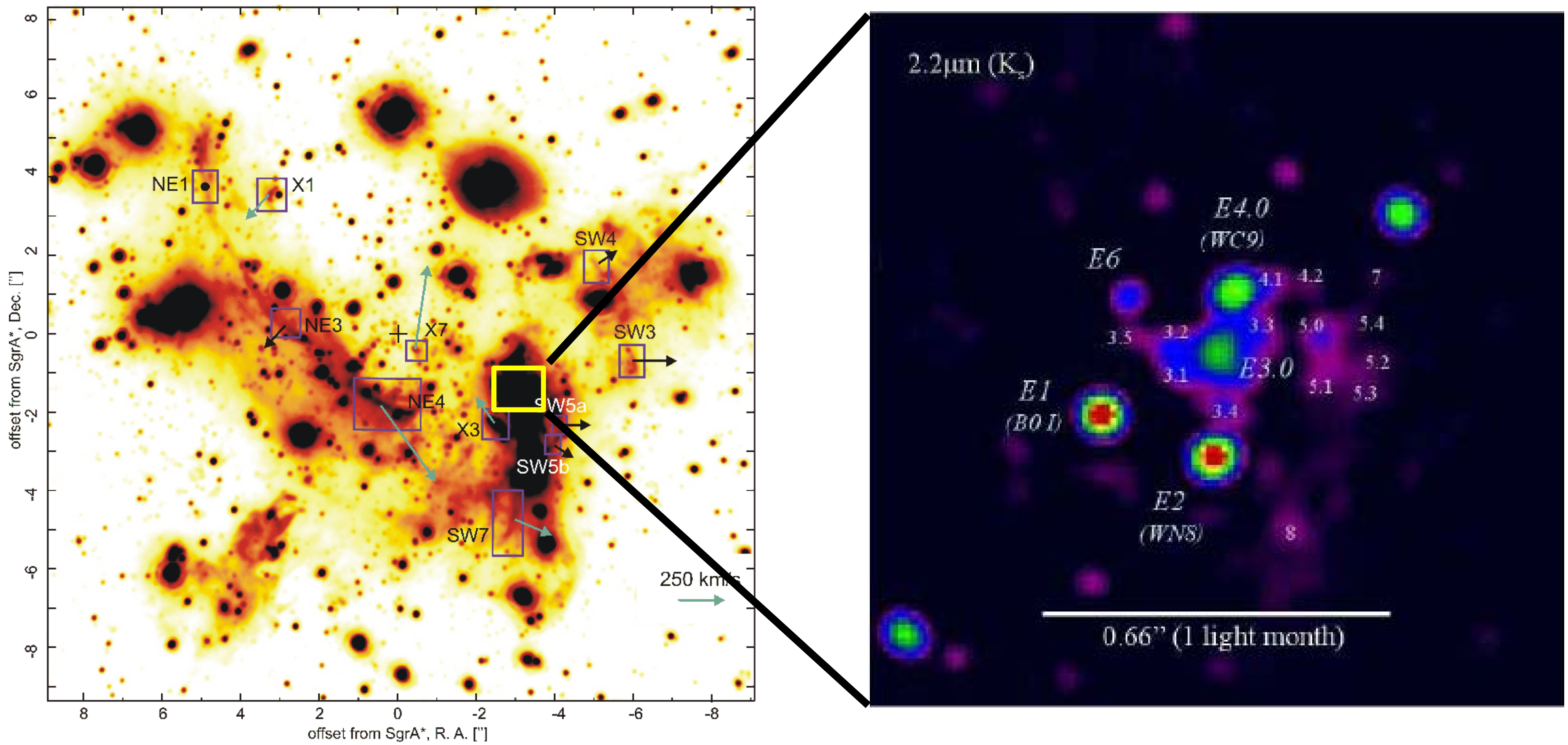
The signature of X-ray binaries in the central 40 pc x 40 pc





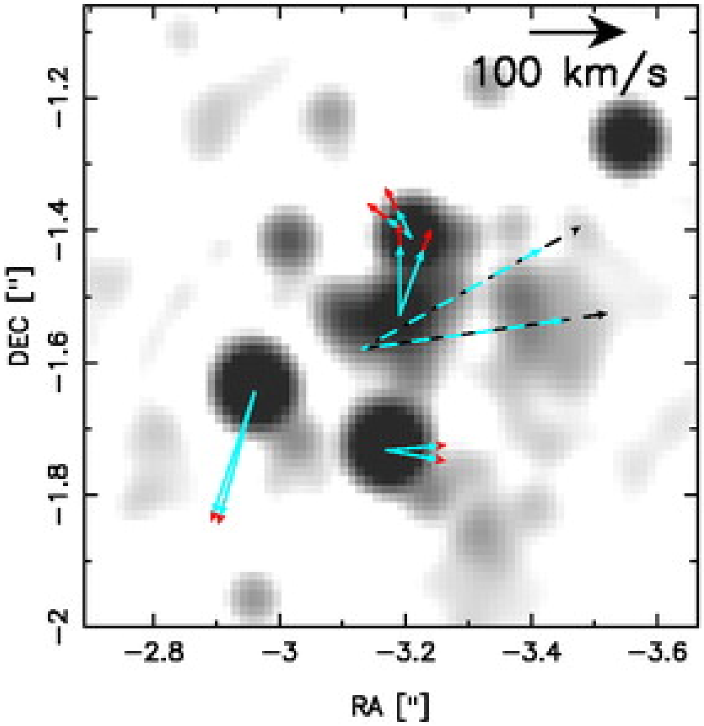
Muno et al. 2003, 2005

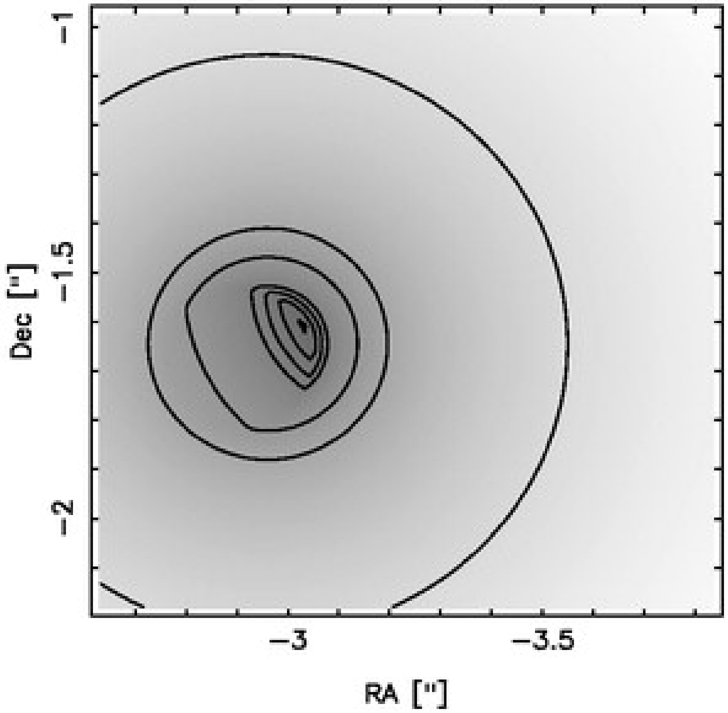
IRS13 E



NE1
X1
SW4
NE3
X7
SW3
NE4
SW5a
X3
SW5b
SW7
250 km/s
offset from SgrA*, Dec. ["]
offset from SgrA*, R. A. ["]
2.2µm (Ks)
E4.0
(WC9)
E6
4.1
4.2
7
3.5
3.2
3.3
5.0
5.4
3.1
E3.0
5.2
E1
(B0 I)
5.1
5.3
3.4
E2
(WN8)
8
0.66" (1 light month)

no IMBH in IRS13 E ?!



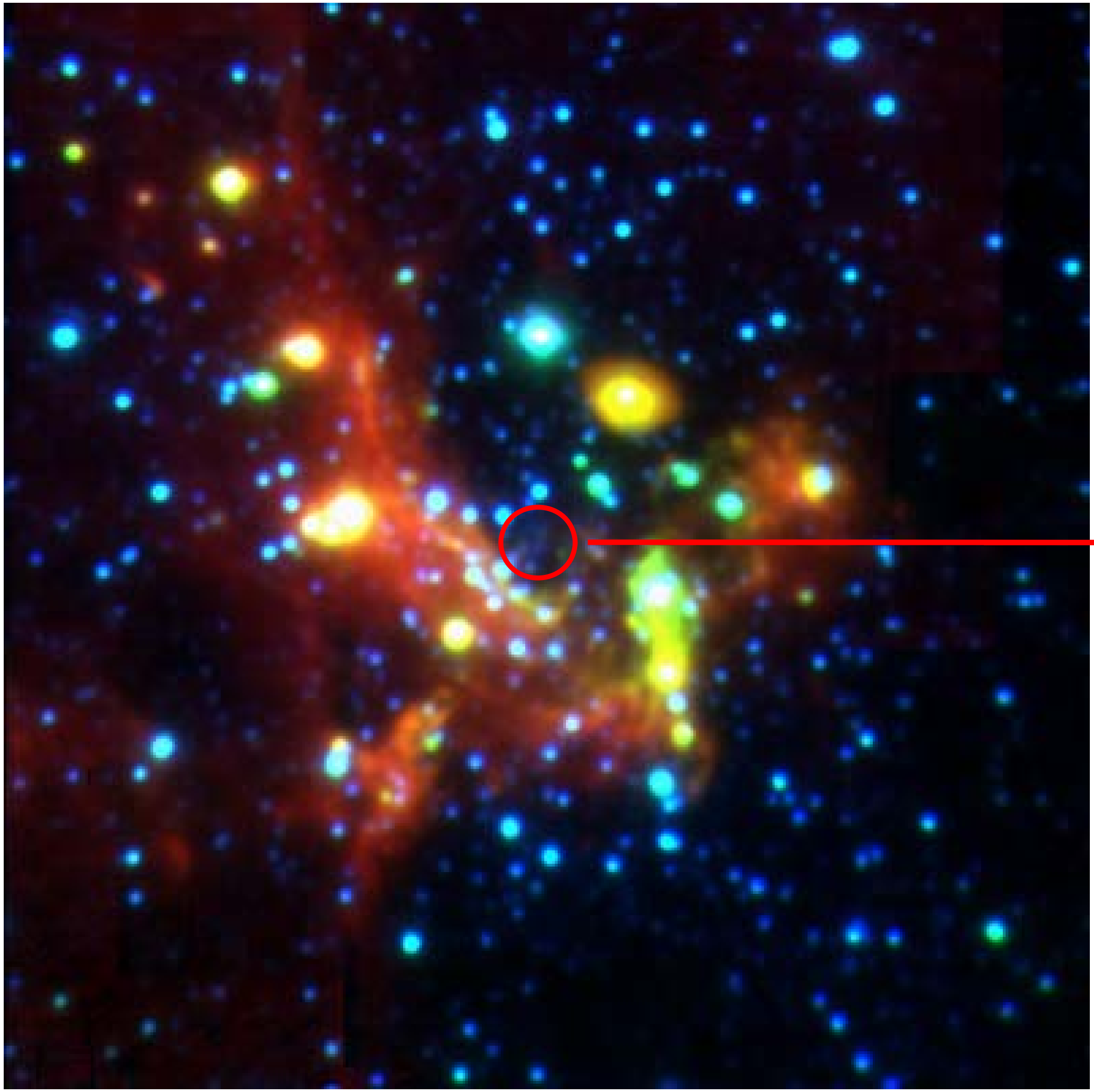


Schödel et al. 2005

upper limit to the intermediate mass black hole :
contours at 7, 8 , 9, 10, 20, 50x10**3 solar masses

see also Fritz et al. 2010: IRS13 E as a chance alingnement

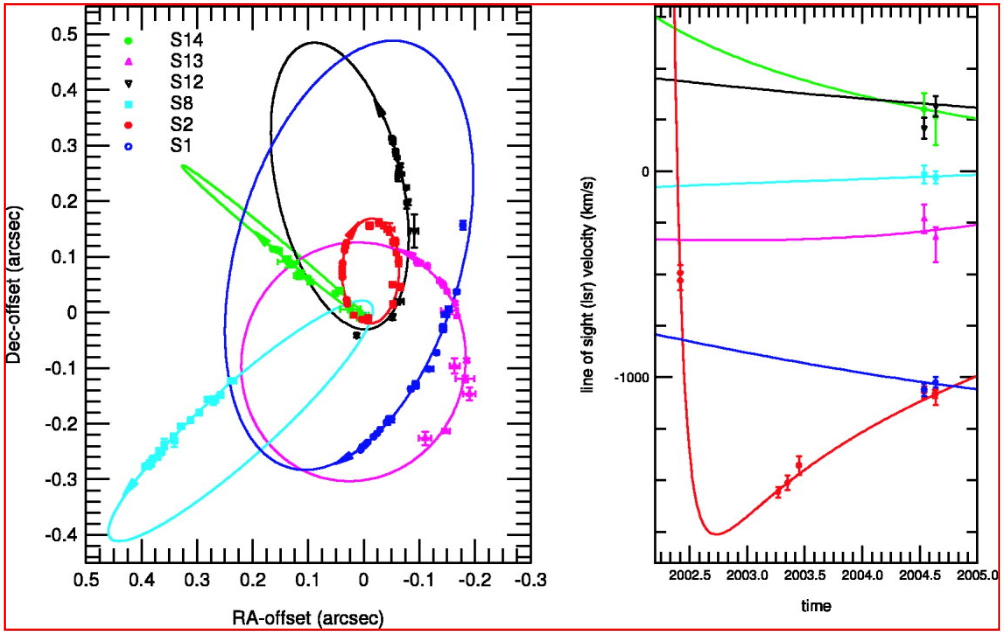
Orbits of High Velocity Stars in the Central Arcsecond

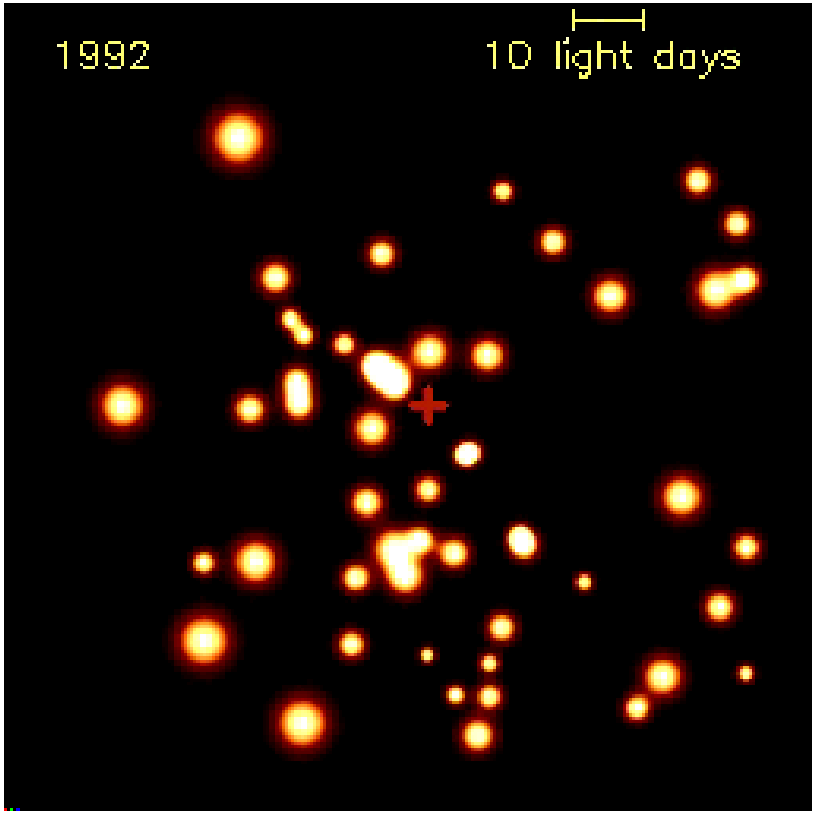


5“ = 0.2 pc

Extreme Physics

Orbits of High Velocity Stars in the Central Arcsecond





Eckart & Genzel 1996/1997 (first proper motions)
Eckart et al. 2002 (S2 is bound; first elements)
Schödel et al. 2002, 2003 (first detailed elements)
Ghez et al 2003 (detailed elements)
Eisenhauer 2005, Gillessen et al. 2009 (improved elements and distance)

~4 million solar masses at a distance of ~8.3+-0.3 kpc

Simultaneous NIR/X-ray Flares

The Synchrotron Self Compton (SSC) model

Investigate the low and high flare states in simultaneous multi wavelength experiments

SgrA* burst in October 2000 in the 2-8 keV band

$R_{S,3\times10^6 M_o} = 9\times10^{11}\ cm$

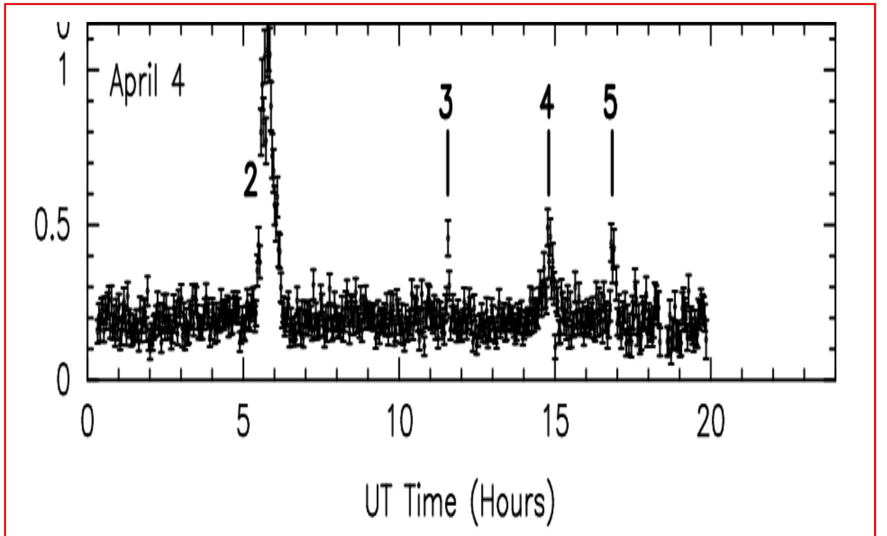
$2.8h \approx 350\ R_S$

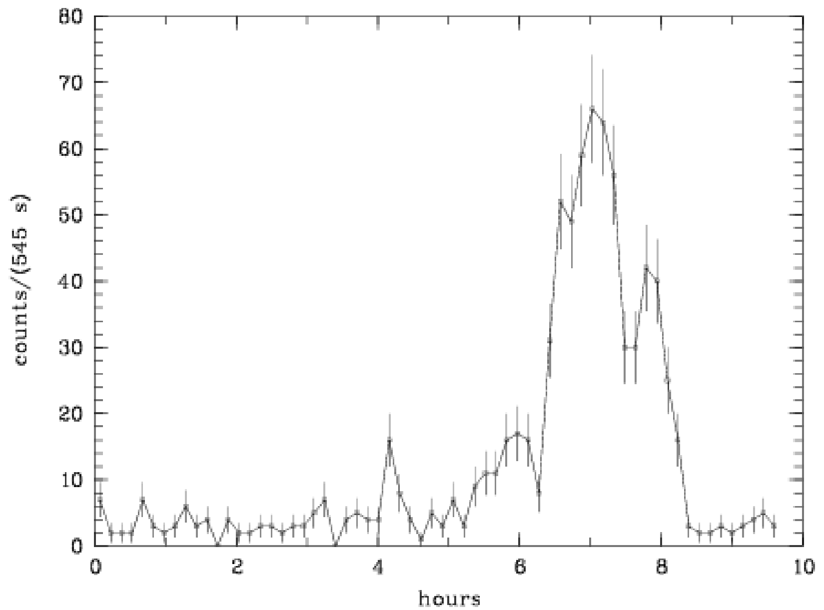
$600\ s \approx 21\ R_S$

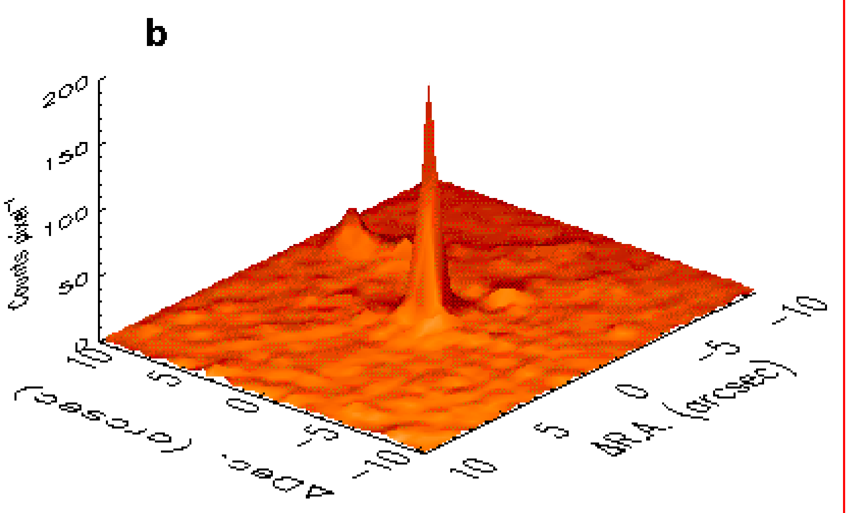
$S_{burst} \approx 50 \times S_{quiescent}$

$1.2 \pm 0.4\ flares\ / day$

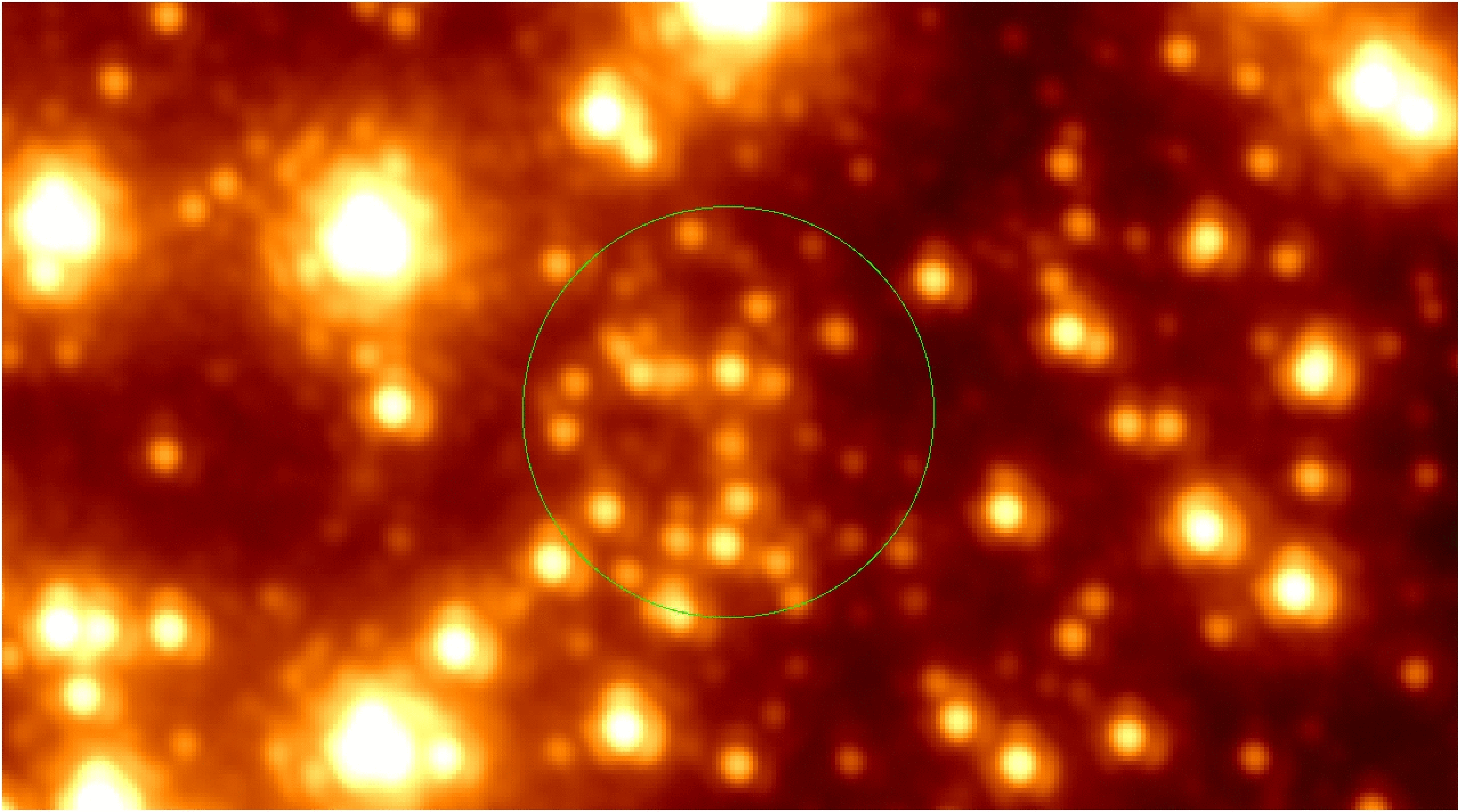
Baganoff et al. 2001, Nature 413, 45







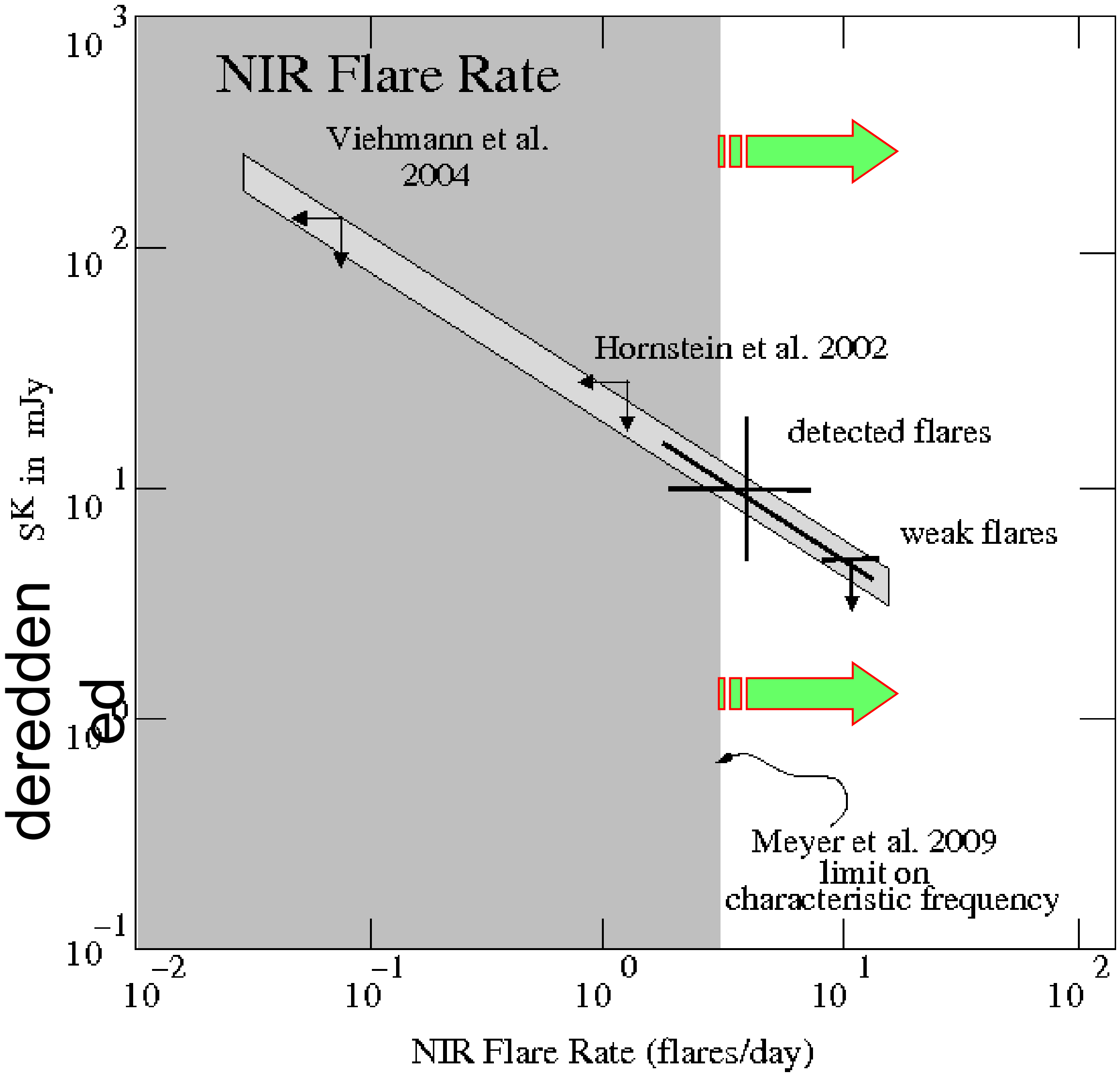
Subtraction of stars within R<0.7''



S<1mJy in the NIR K-band

Sabha et al. 2010

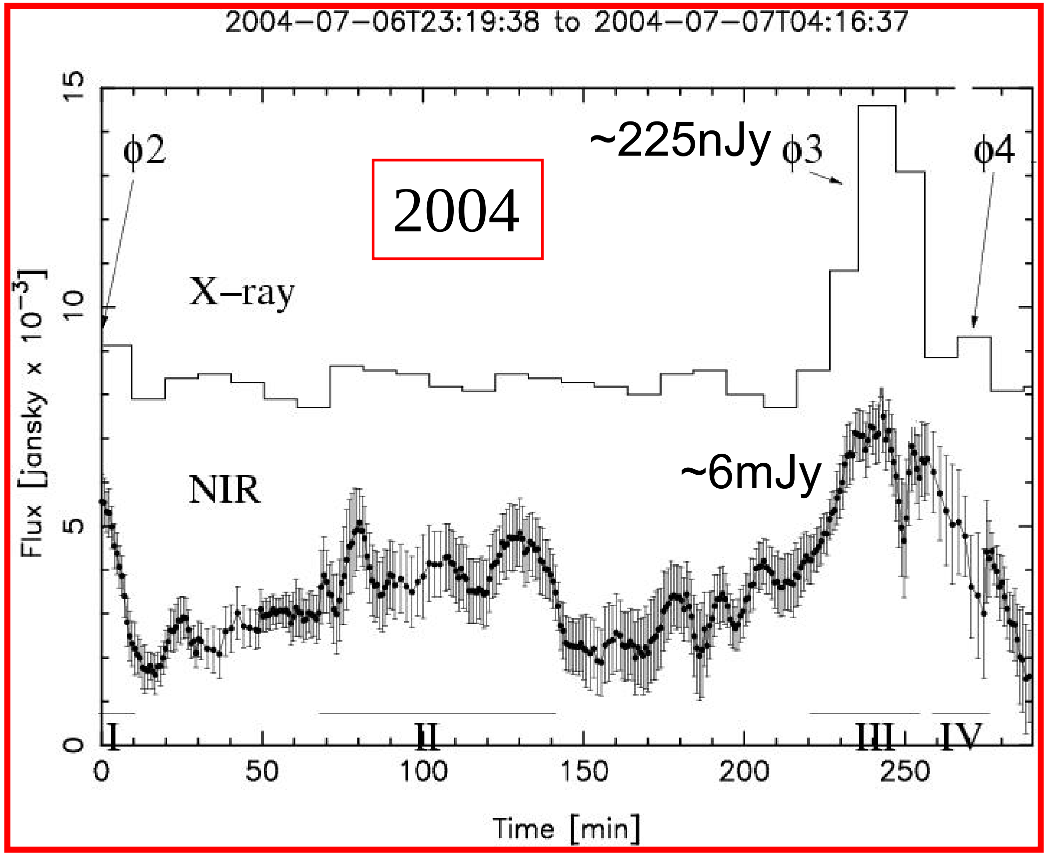
NIR K-band Flare Rate

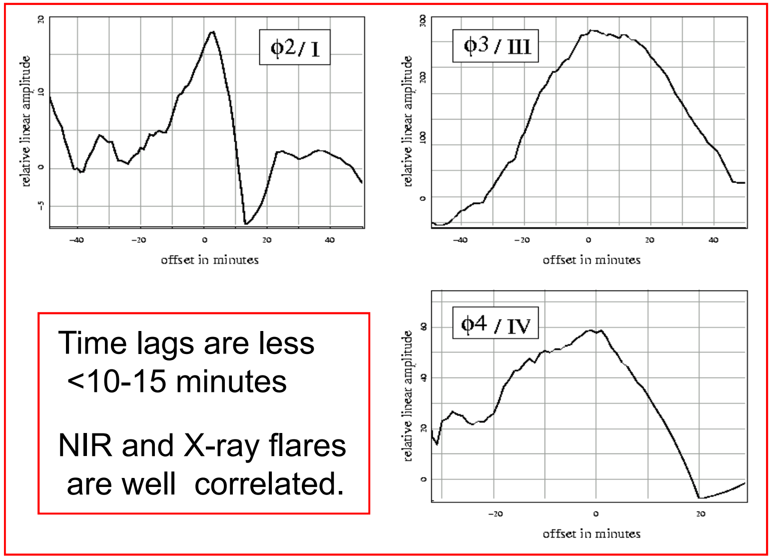


The observed
K-band rate of
4-8 flares/day
Brighter than about
3 mJy is consistent
With the upper limit
On the characteristic
frequency of
flares from light
curve modeling
(Meyer et al. 2009);

Red noise:
Do et al. 2008;
Pechacek et al. 2008;
Eckart et al. 2006;

Simultaueous NIR/X-ray Flare emission 2004



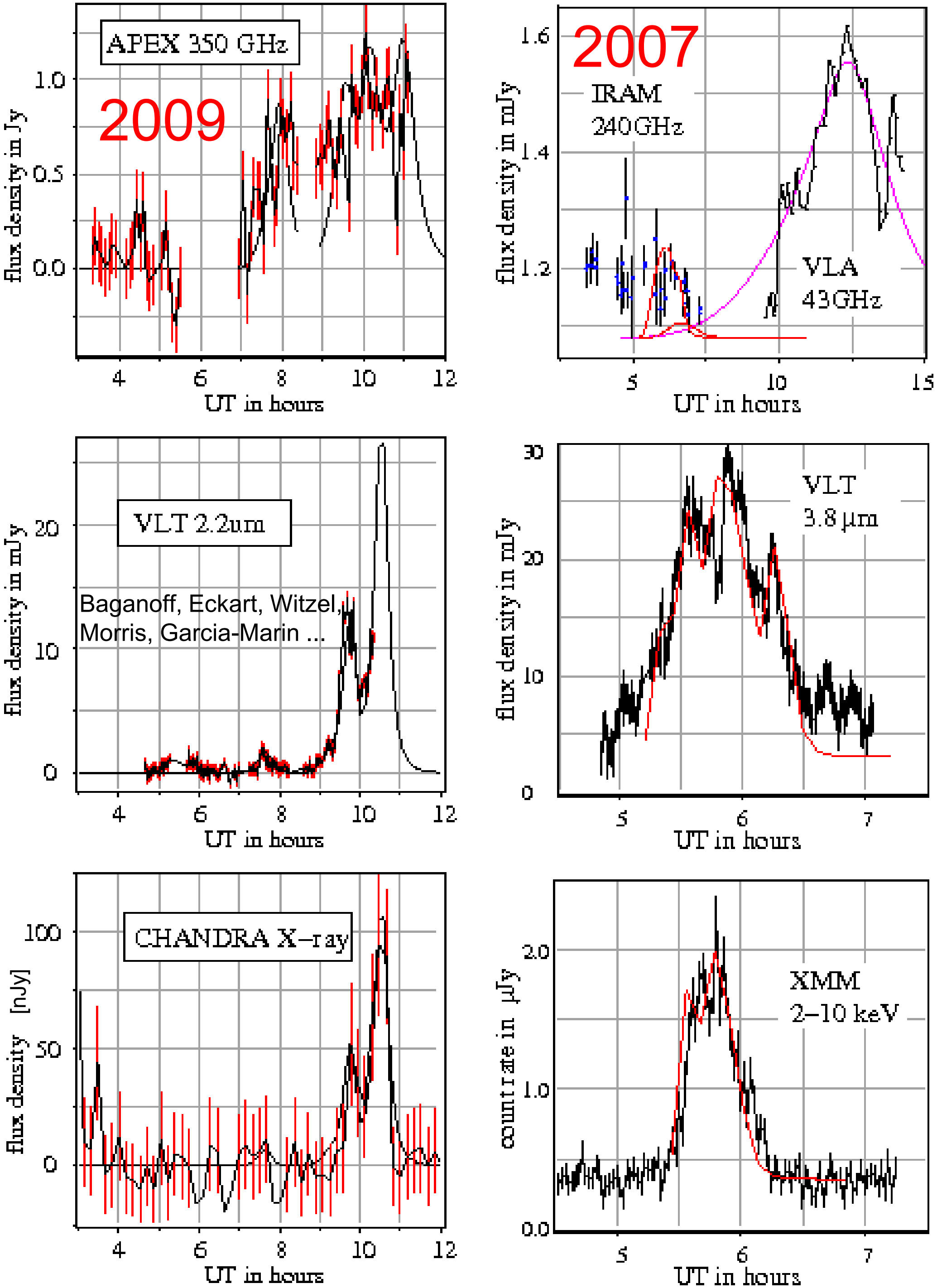


Flare emission originates from within <10mas form the position of SgrA*

First simultaneous NIR/X-ray detection
2003 data: Eckart, Baganoff, Morris, Bautz, Brandt, et al. 2004 A&A 427, 1
2004 data: Eckart, Morris, Baganoff, Bower, Marrone et al. 2006 A&A 450, 535

see also Yusef-Zadeh, et al. 2008, Marrone et al. 2008

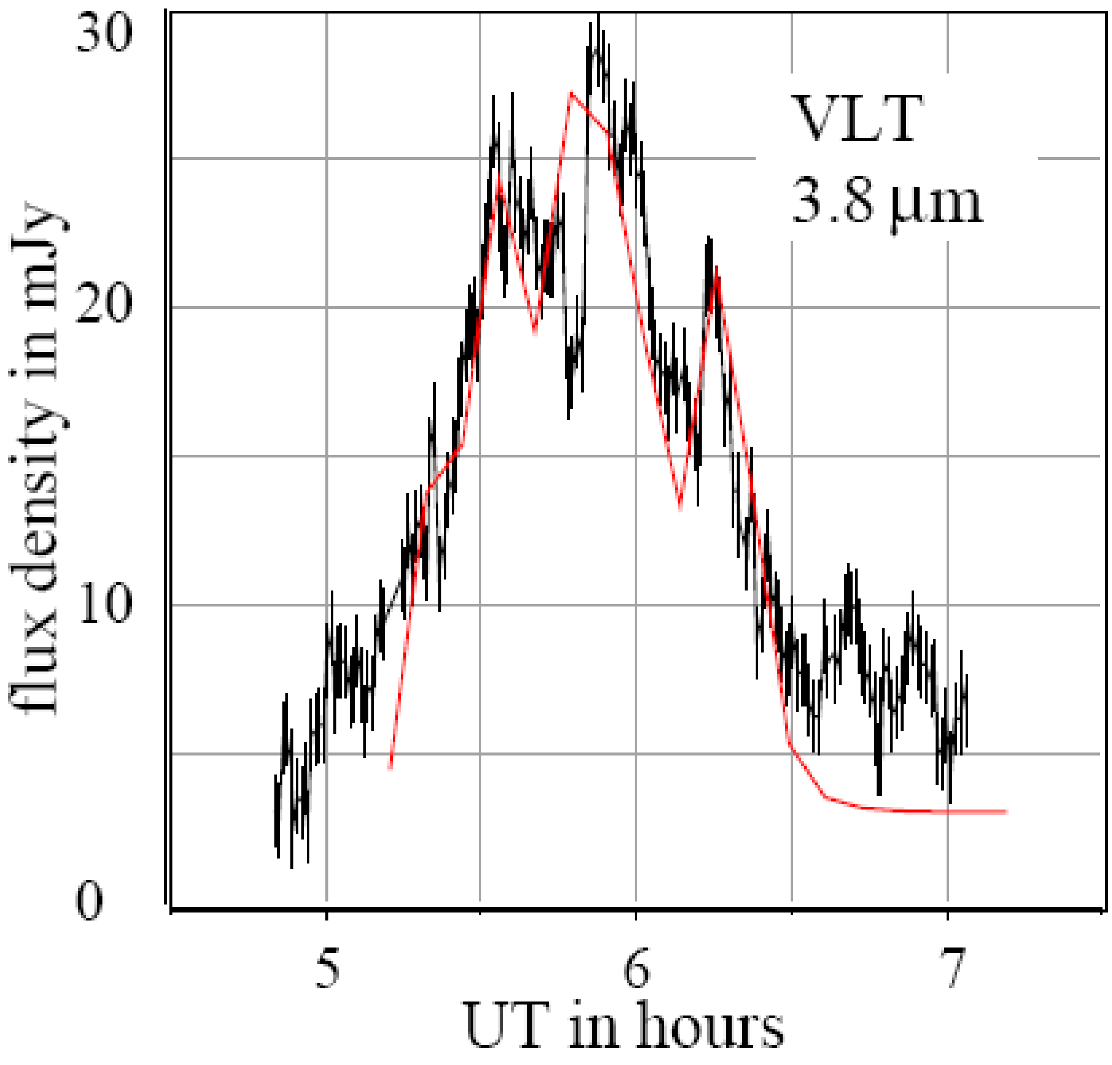
Simultaneous NIR/X-ray flares



Porquet et al. 2008
Dodds-Eden et al. 2009, 2010
Yusef-Zadeh et al. 2009

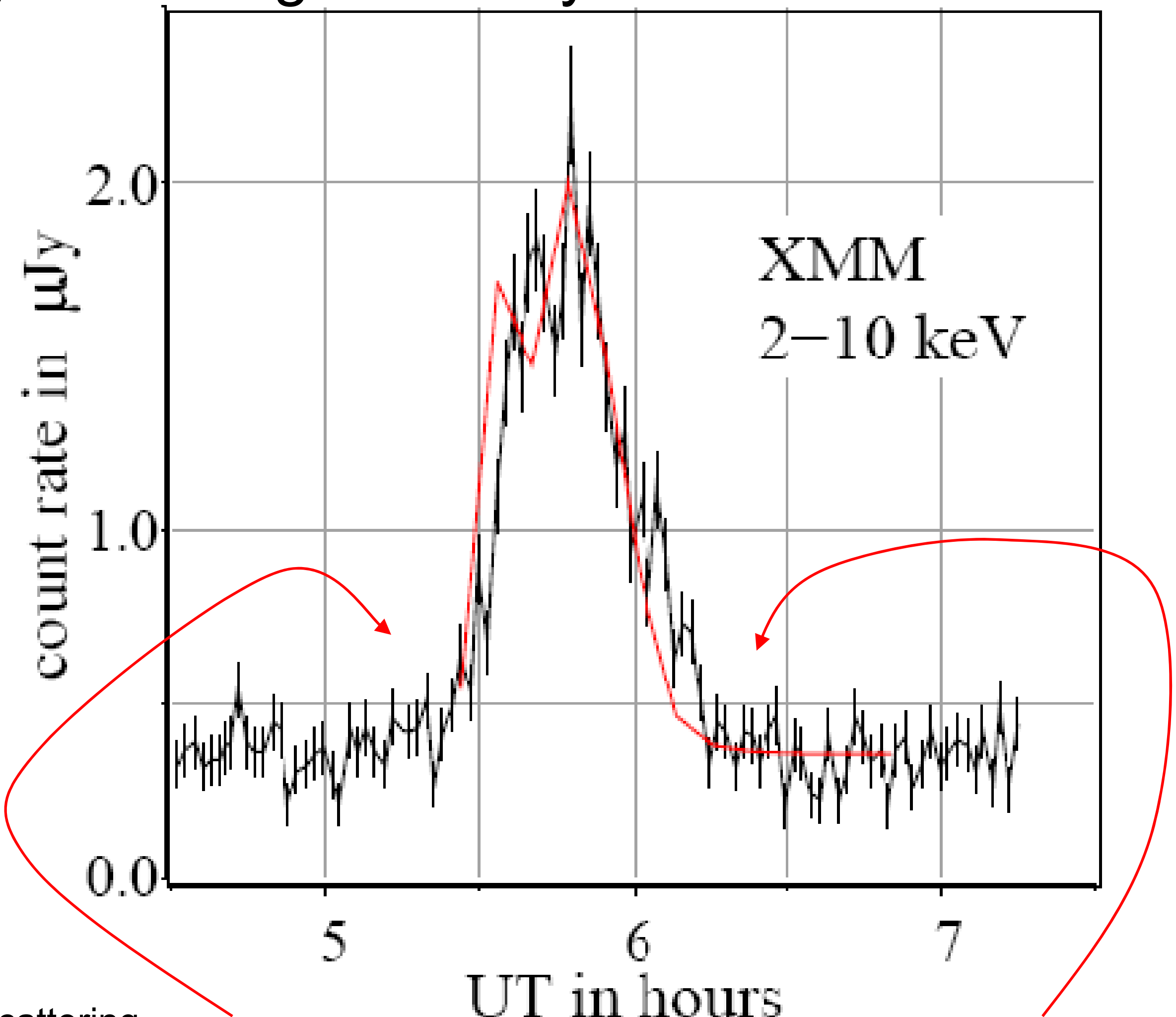
Sabha et al. 2009

High Power X-ray Flare: VLT



High Power X-ray Flare: XMM

X-ray scattering efficiency:



A 25% smaller S_m or larger θ results in the required decrease in scattering efficiency and a 3 times lower B during the bright flare phase.

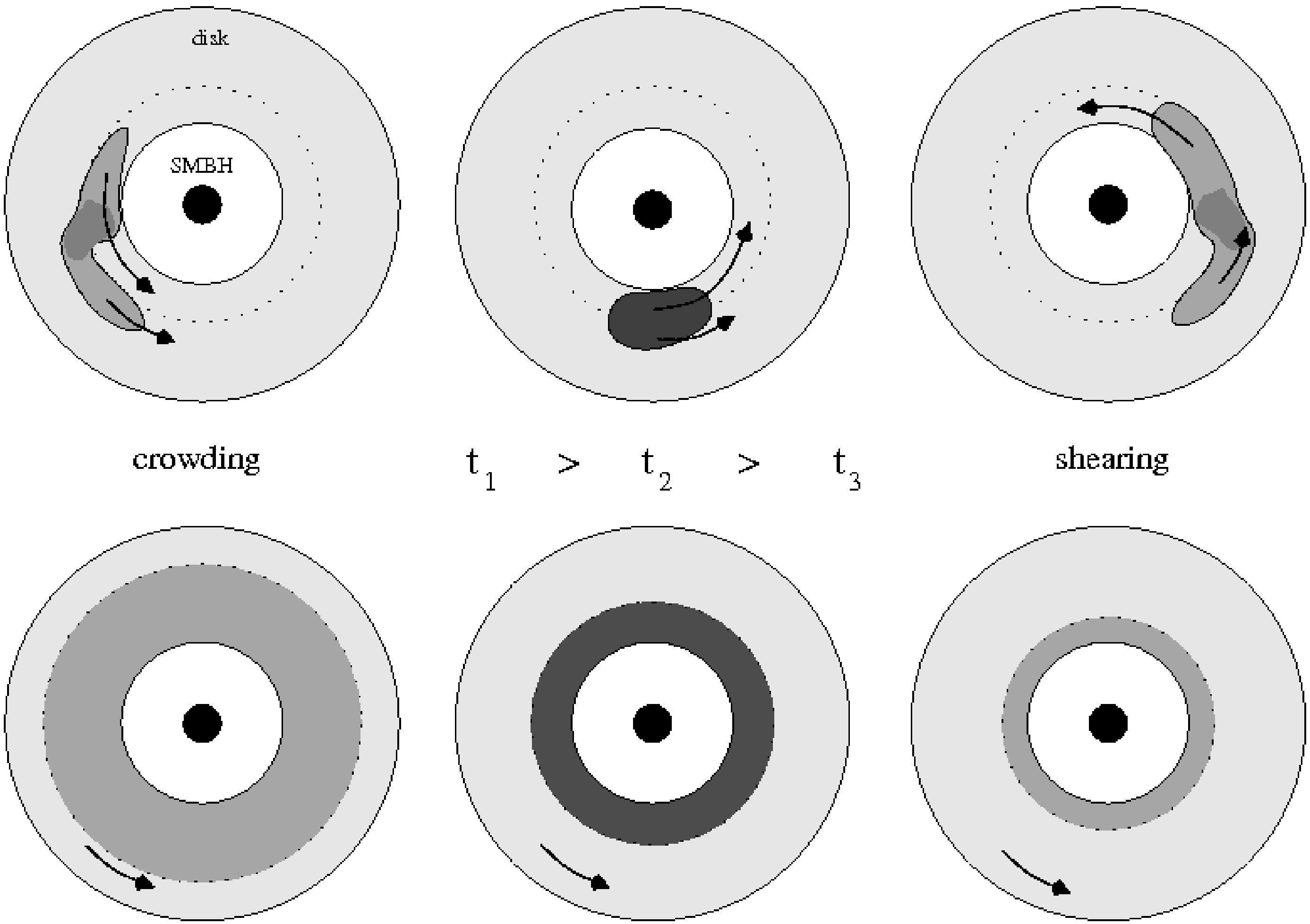
$$S_\nu^{SSC}(E_{keV}) \propto \theta^{-2(2\alpha+3)} S_m^{2(\alpha+2)}$$

$$B \propto \theta^4 S^{-2}$$

High Power X-ray Flare: Model

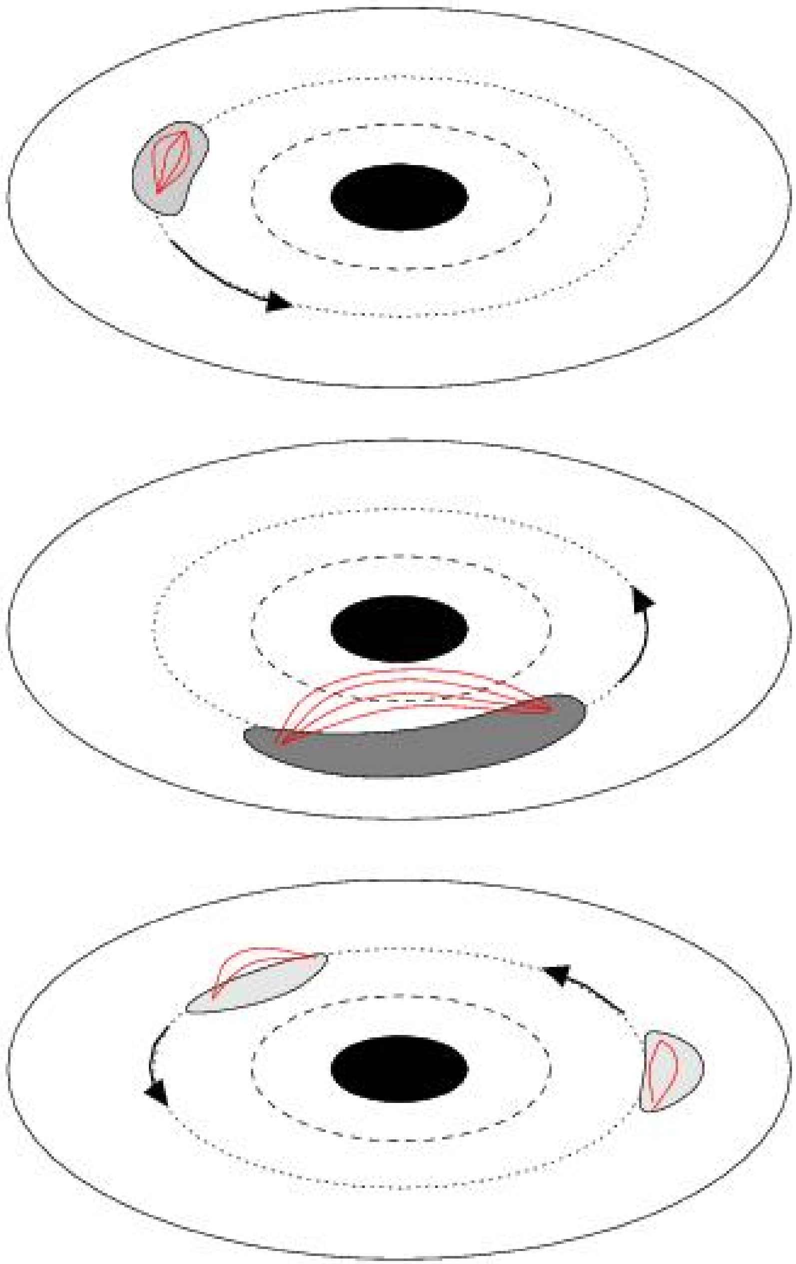
SSC X-ray scattering efficiency:

low | high | low

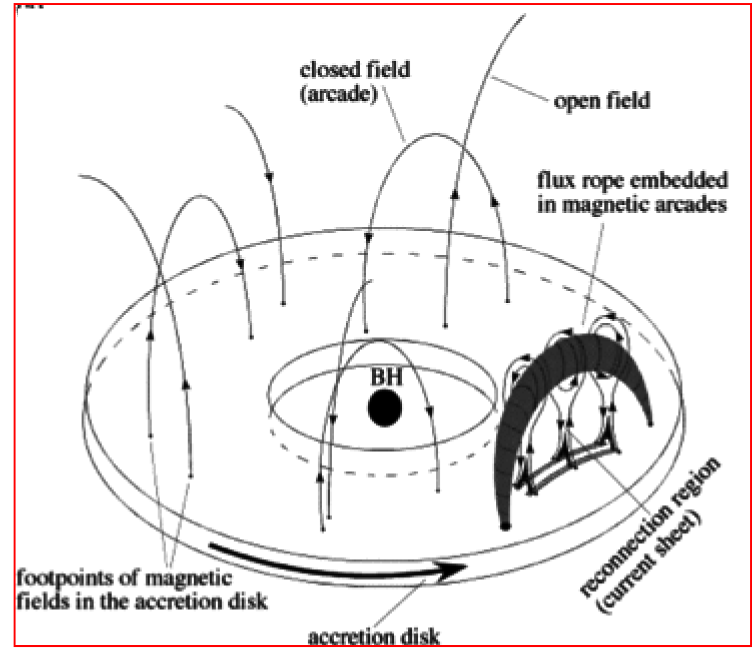


differentially rotating disk Eckart et al. 2008; Hawley & Balbus 1991, 1998

axisymmetric wave oscillation e.g. Chan et al. 2009

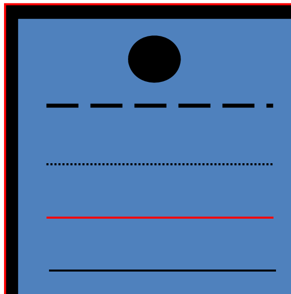


Yuan et al. 2009, Balbus & Hawley 1998, Balbus 2003



Yuan et al. 2009

Adiabatic Expansion of Source Components in the Temporary Accretion Disk of SgrA*



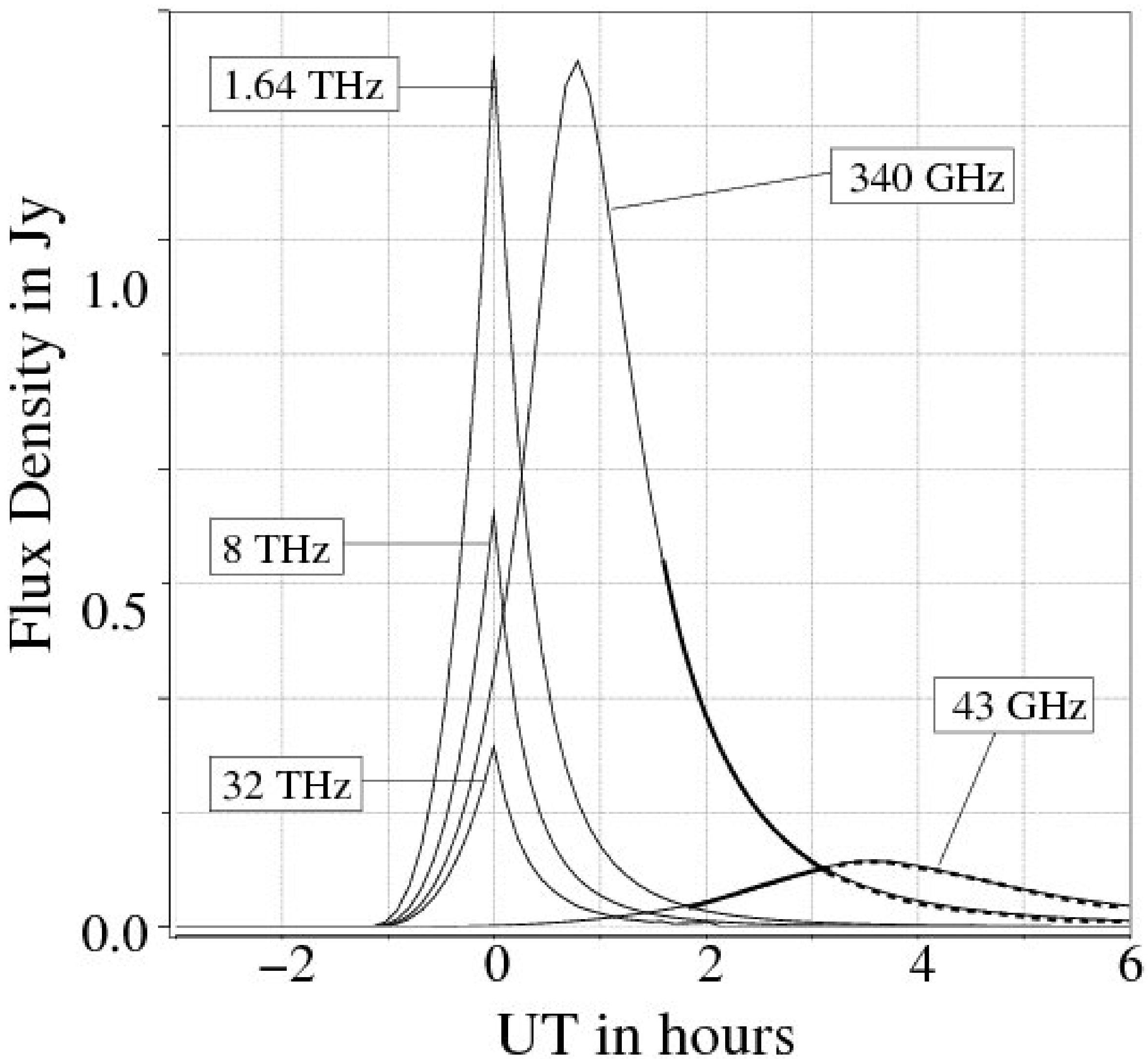
Black Hole
Last stable orbit
reference orbit
magnetic field lines
outer edge of disk

Eckart et al. 2008, ESO Messenger
Eckart et al. 2009, A&A 500, 935

Indication for Adiabatic Expansion of Synchrotron Source Components

Trace the flares at highest frequencies close to the synchrotron turnover frequency

Adiabatic Expansion of a Single Synchrotron Source Component



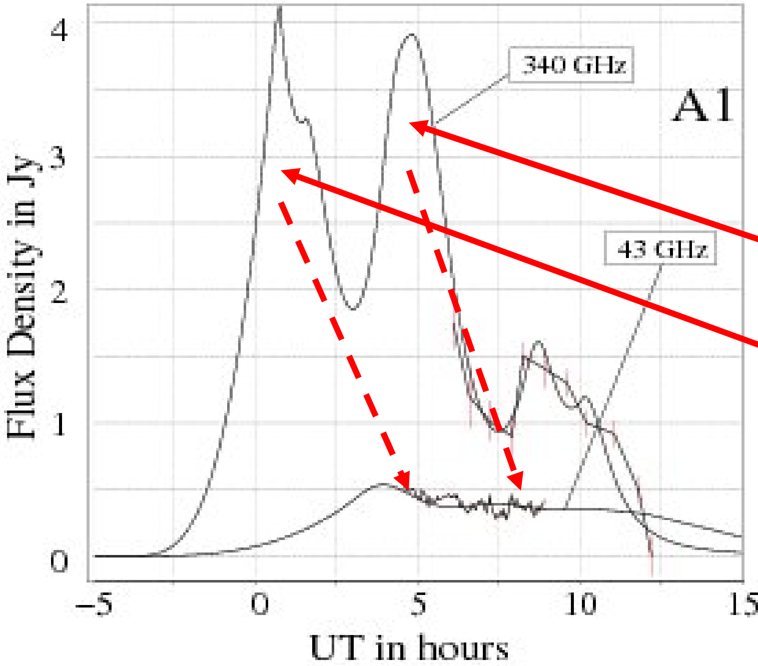
Peak Flux Density
10 Jy
Peak Frequency
1.64 THz
Assumed
Expansion Velocity
V = 0.008 c

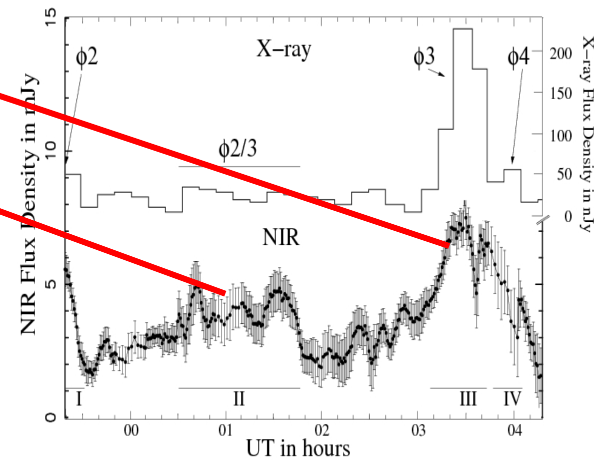
Expansion speed
close to the disk:
Yuan et al. 2008
Liu et al. 2006

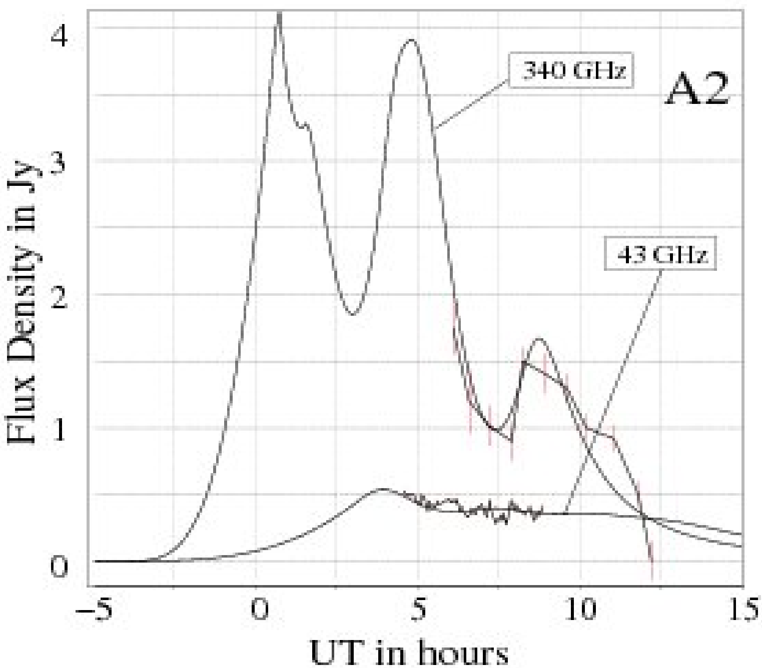
See also
Yusef-Zadeh et al.
2006-2009

Eckart et al. 2009
A&A 500, 395

2004: First Quasi Simultaneous X-ray/NIR/radio measurements







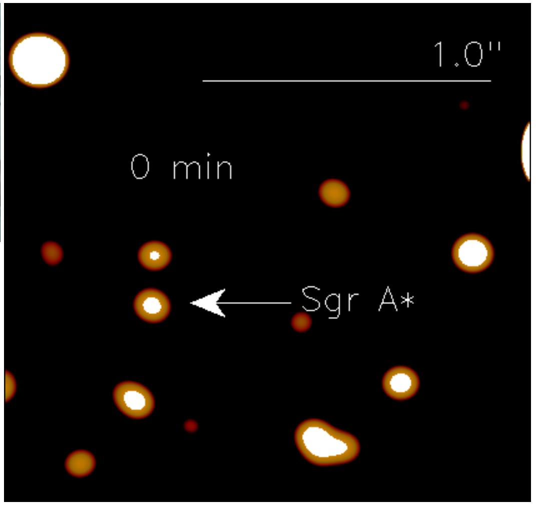
Adiabatic Expansion Model for the 7 July 2004 Flare

A total of 3-6 source components allow for a complete fit of the variable part of the SMA and VLA data.

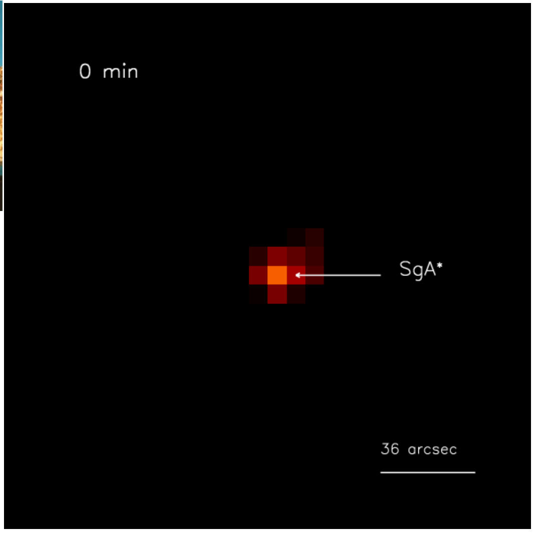
We find 0.005-0.008c as a suitable expansion velocity - consistent with Yusef-Zadeh's values of 0.003-0.1 c and Yuan et al. 2008

Eckart et al. 2009; A&A 500, 395

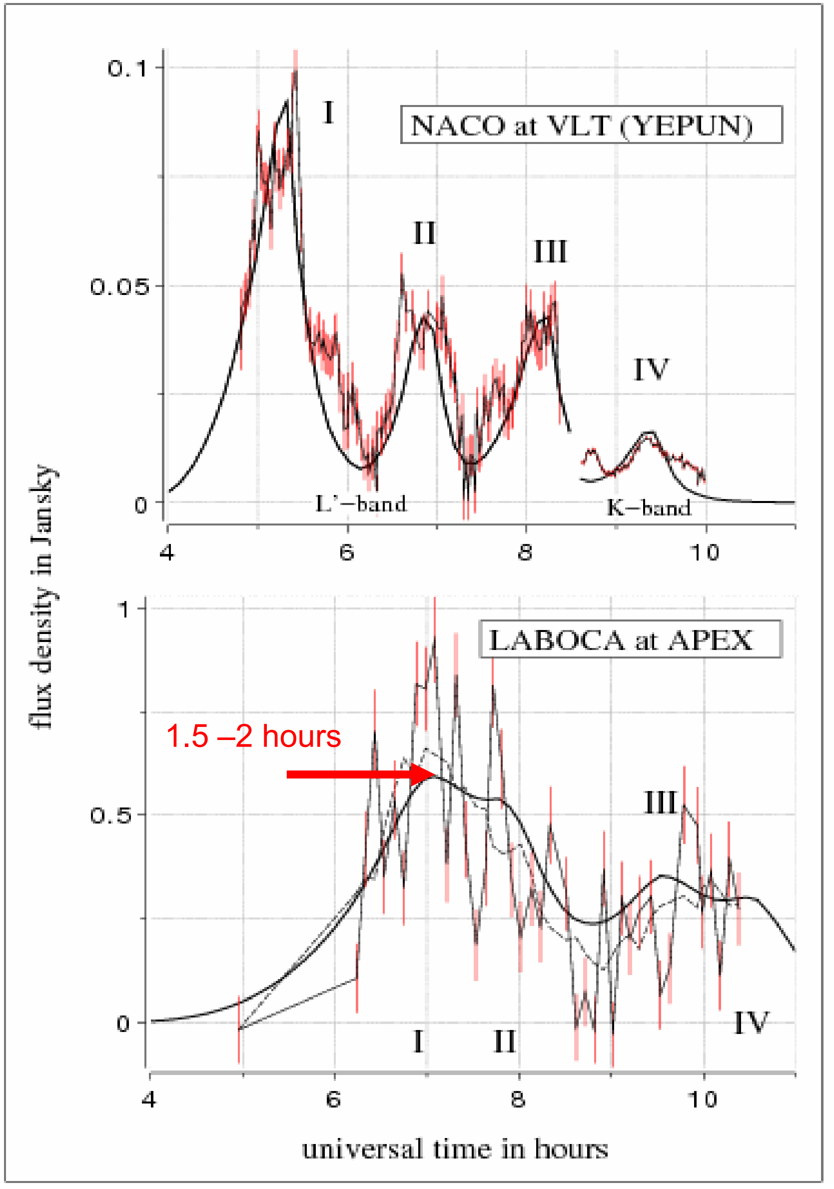
SgrA* on 3 June 2008:
VLT L-band and APEX
sub-mm measurements



VLT UT4
L-band



APEX
1.3 mm



v(exp) = 0.006 c
Eckart et al. 2008; A&A 492, 337
1.5 – 2 hours lag between NIR/sub-mm

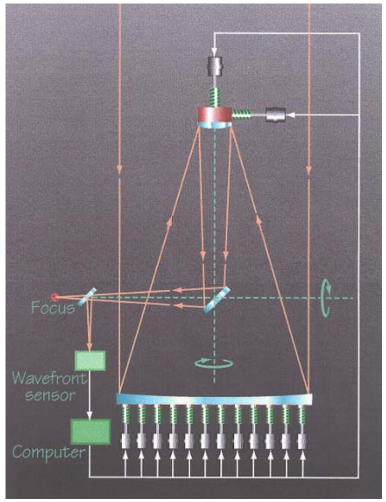
Polarized NIR Emission from SgrA*:
The sub-flares are polarized!

Significance of polarized flares
against red noise
indication for strong gravity

polarization data are consistent with
the orbiting spot hypothesis

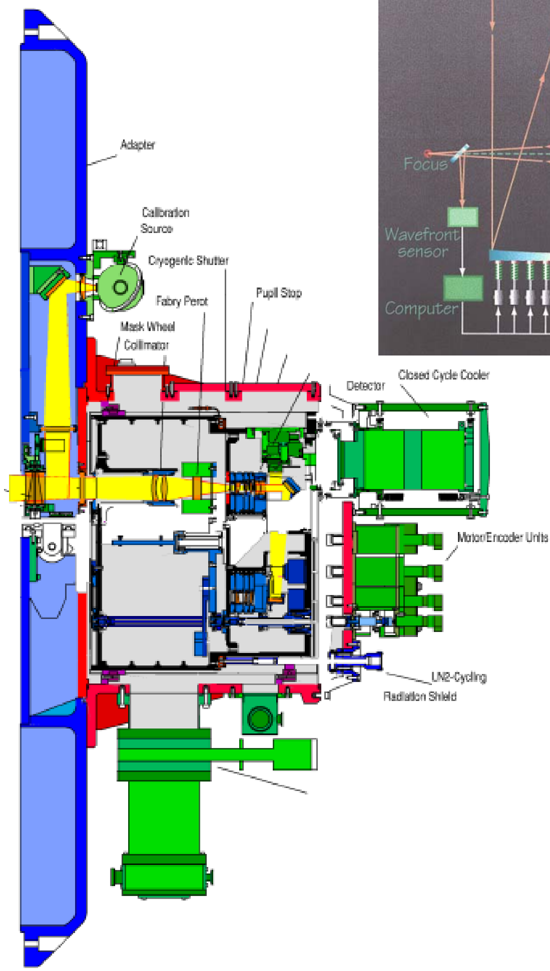
Determine flux density contributions of the
disk and jet at sub-mm wavelengths

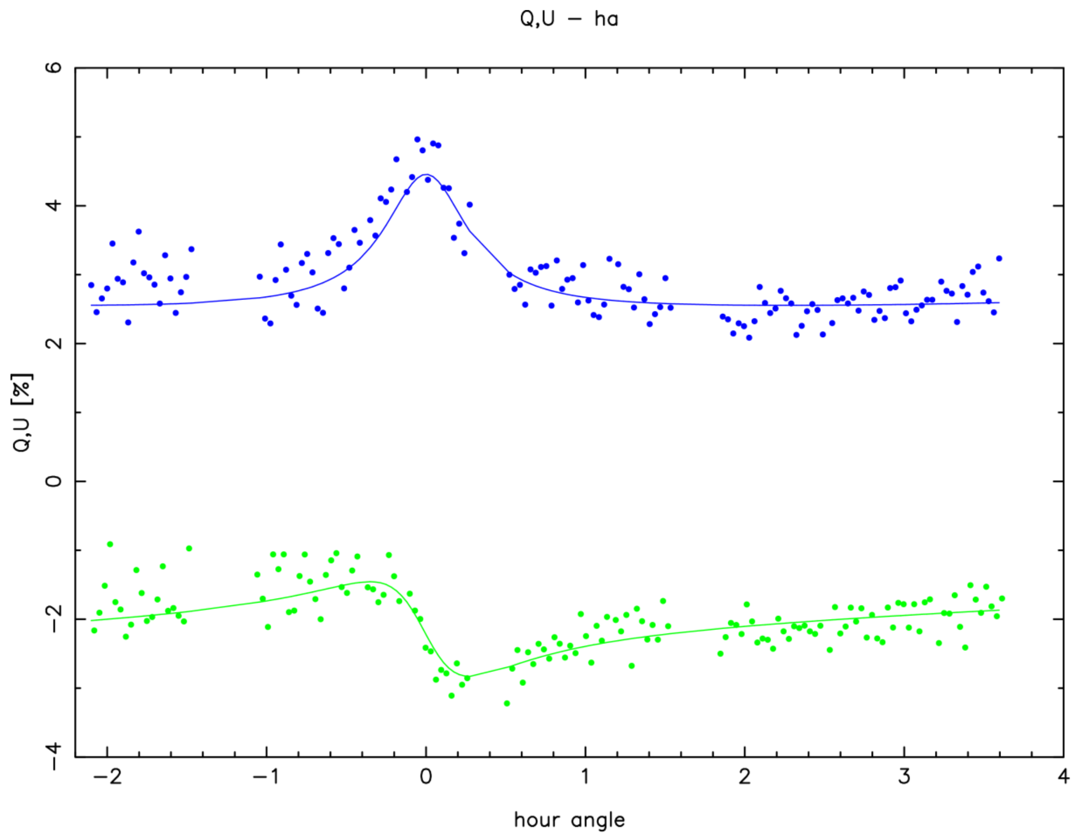
Precision of NIR Polarization measurements



Instrument calibrated to ~1%

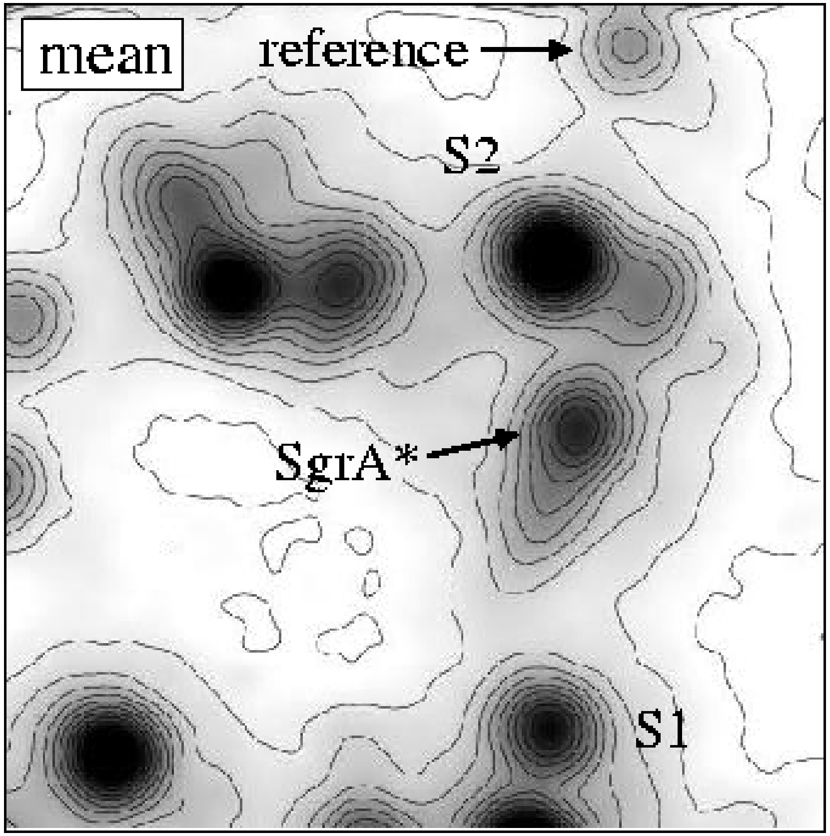
Current limit due to systematics ~3-4%

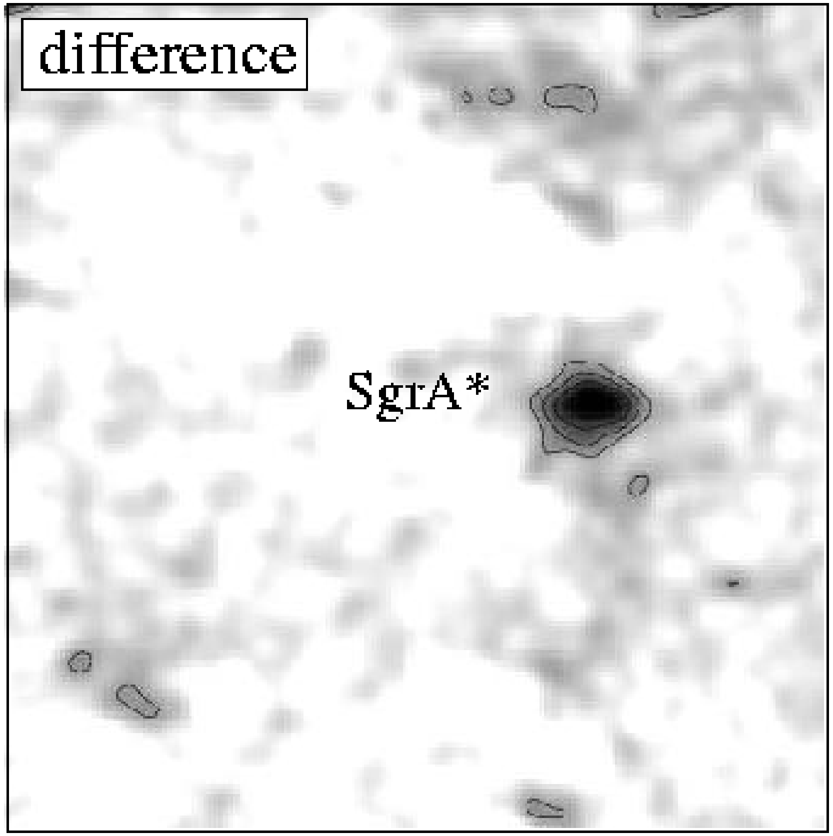




Witzel, G., et al. 2010 sumitted.

Precision of NIR Polarization measurements

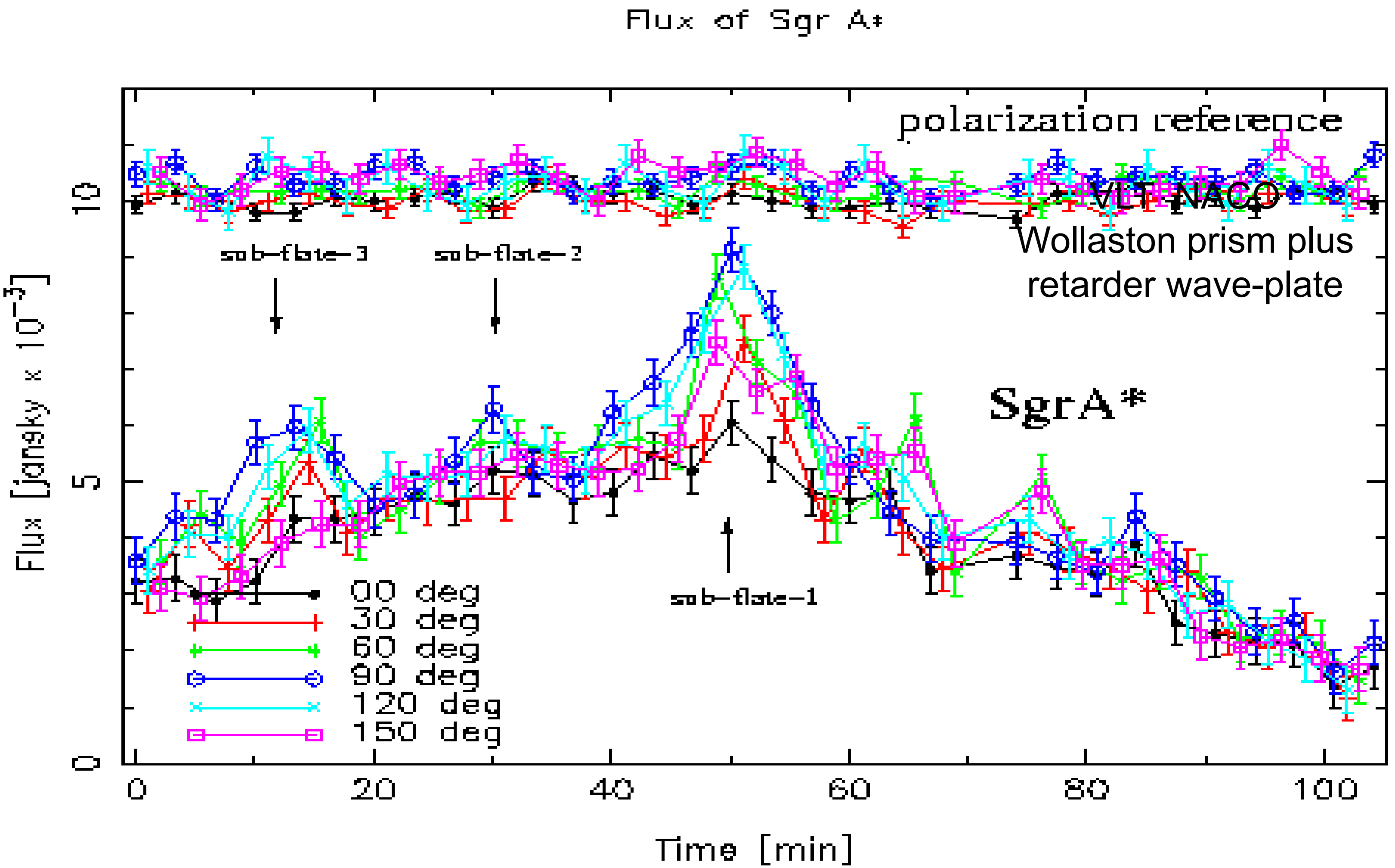




mean flux at 0 and 90 degrees difference between flux at 0 and 90 degrees

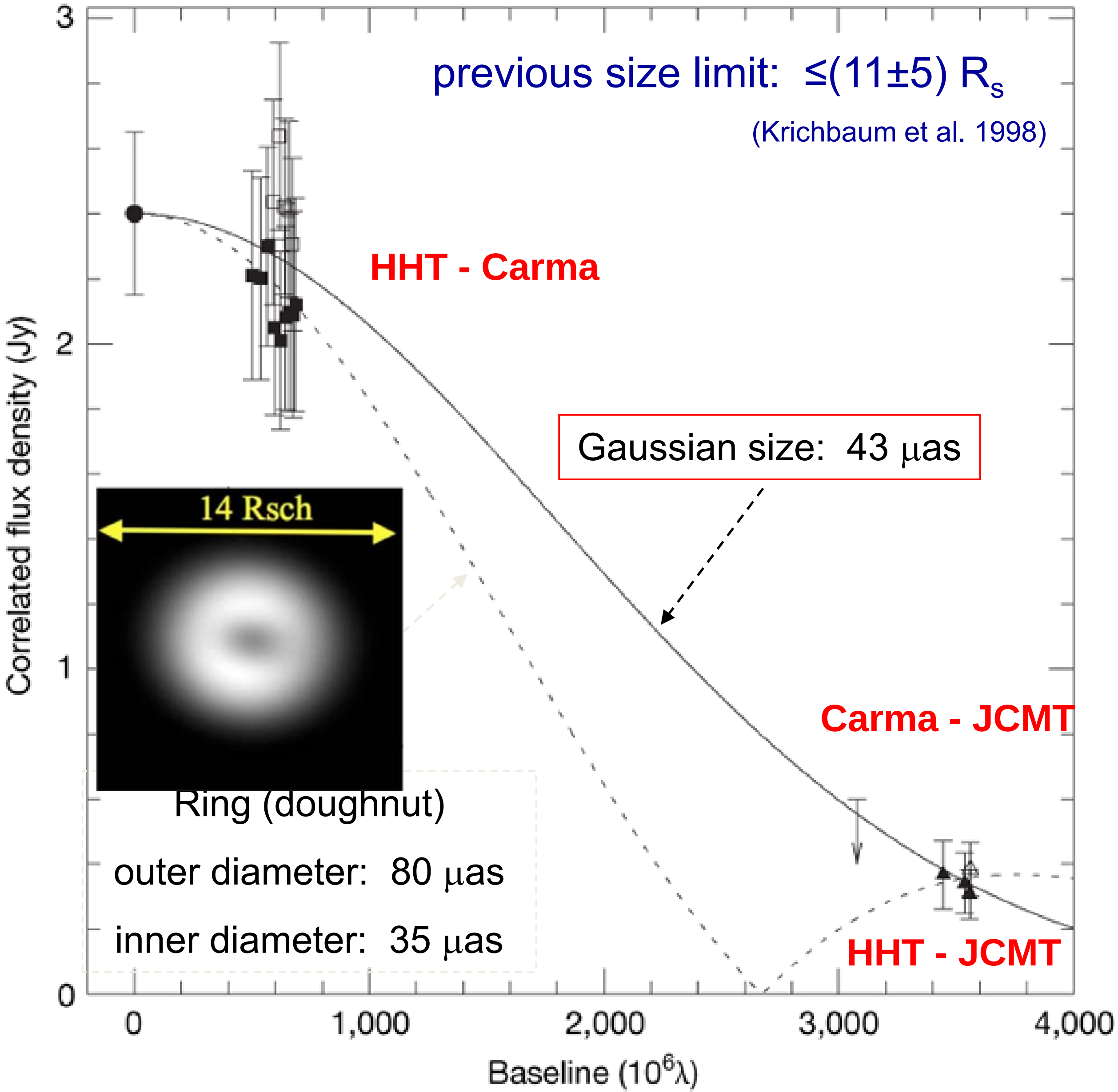
July 2005: VLT NACO Wollaston prism plus λ/2 retarder wave-plate

NIR Polarized Flux Density from SgrA*

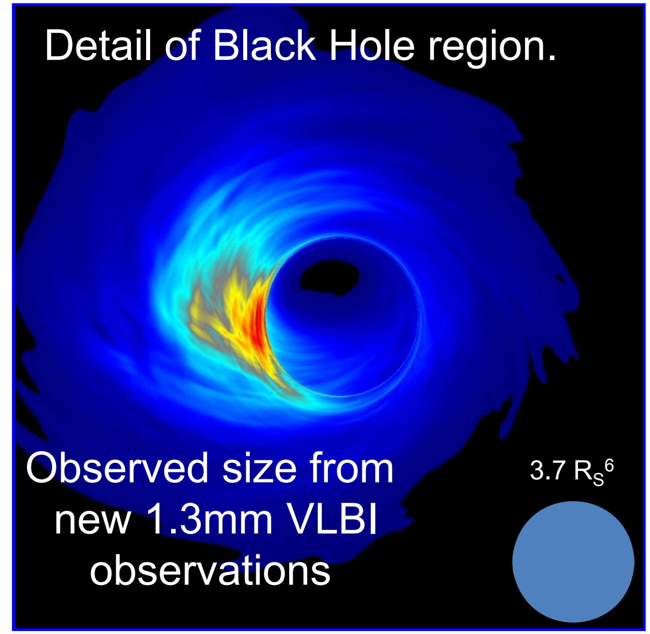


Eckart, Schödel, Meyer Trippe, Ott, Genzel
2006, A&A 455, 1

VLBI at 230 GHz (1.3 mm wavelength)



Doeleman *et al. Nature* **455**, 78-80 (2008)



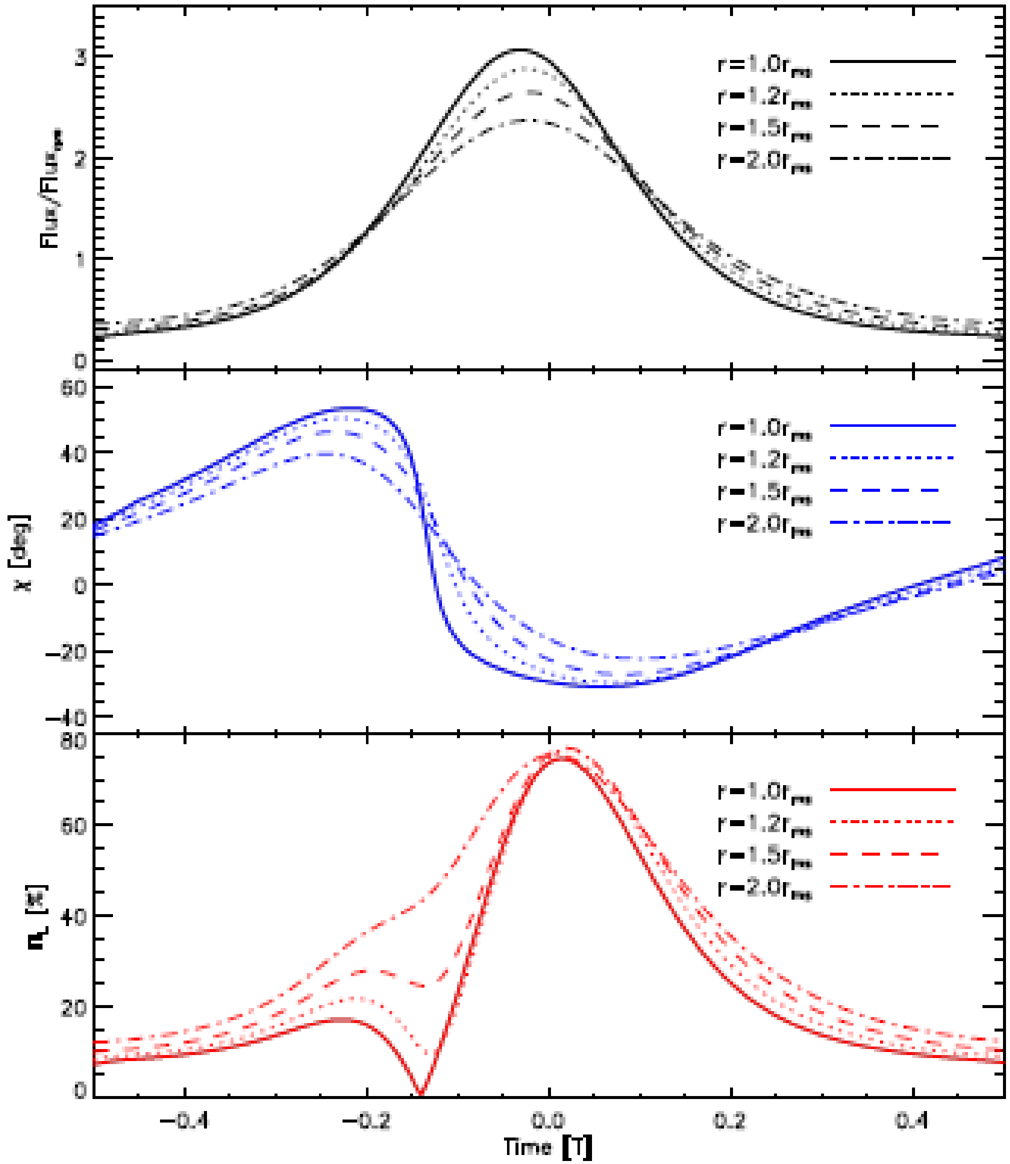
observed size:

43 (+14/-8) μas

deconvolved :

37 μas (3.7 R_S)

Pattern of a NIR spot orbiting at the ISCO



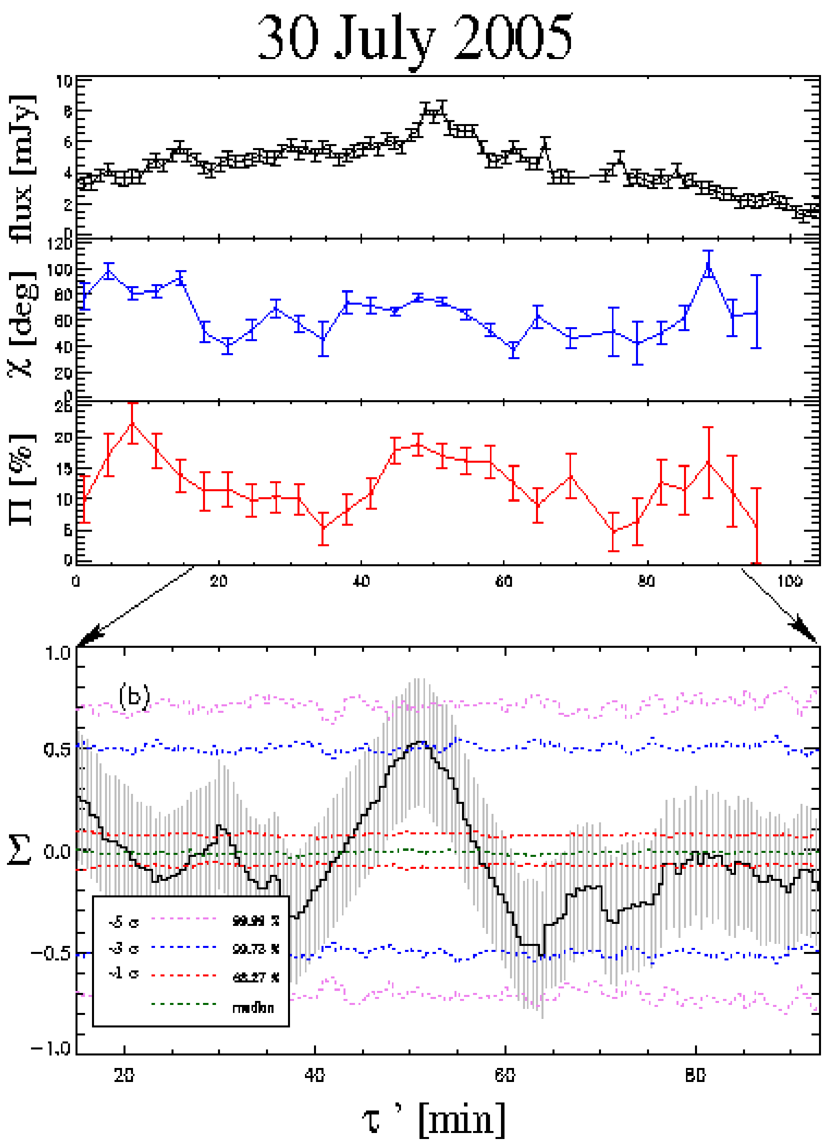
total intensity

polarization angle

polarization degree

Zamaninasab et al. 2009

Pattern recognition against polarized red noise



total intensity

polarization angle

polarization degree

5σ

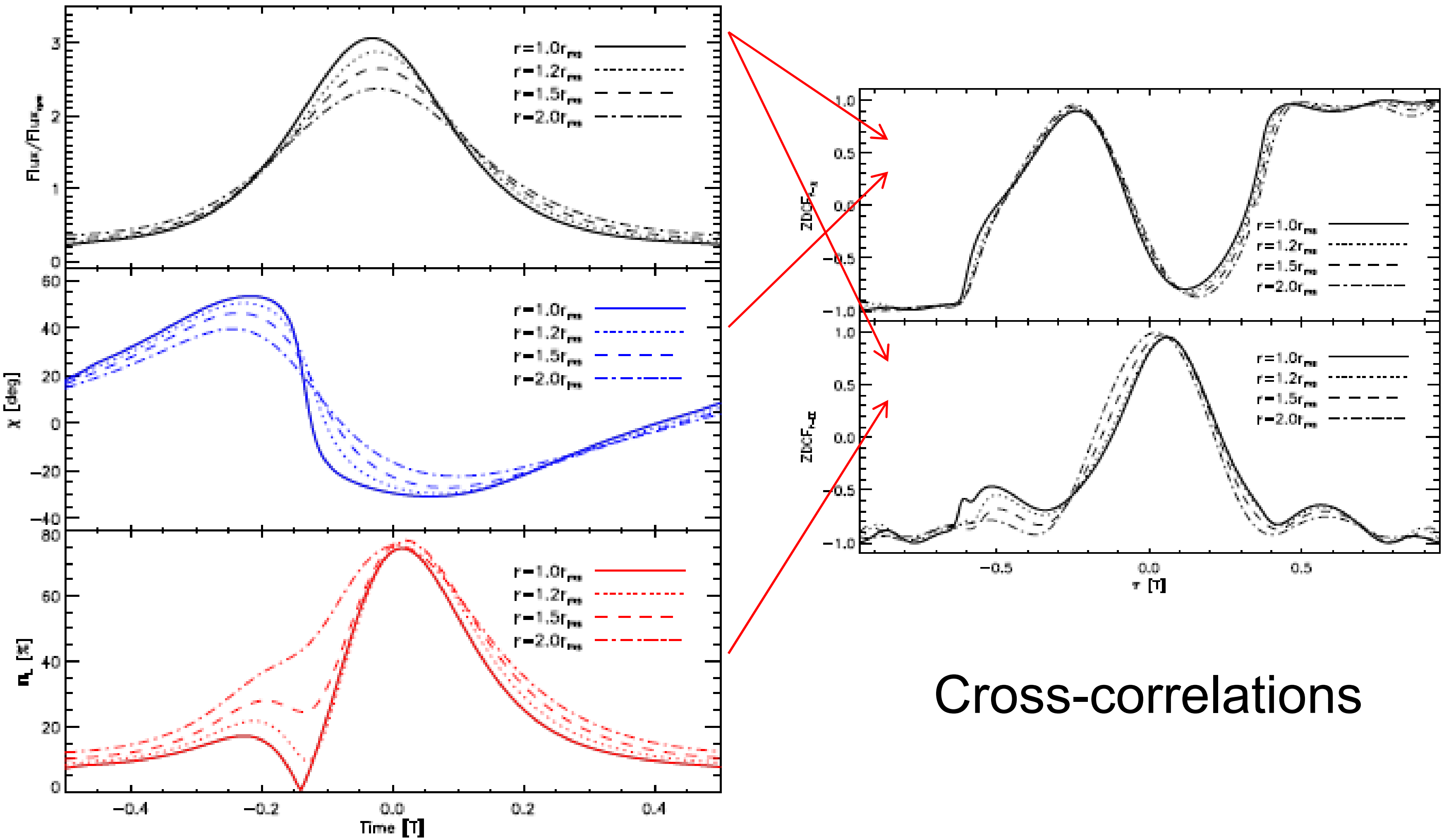
3σ

1σ

mean

Zamaninasab et al. 2009

Pattern of a spot orbiting at the ISCO



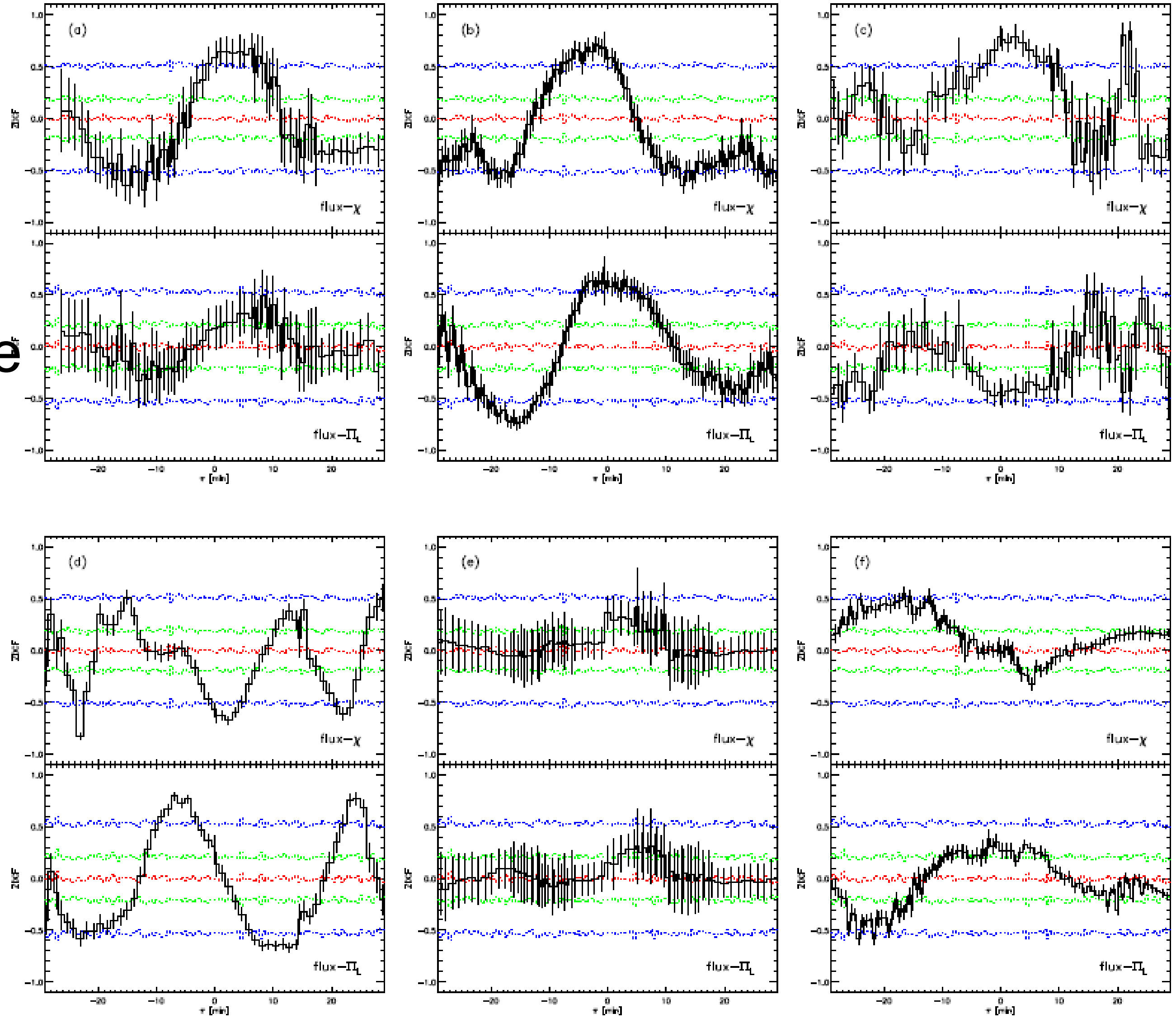
Cross-correlations

Zamaninasab et al. 2009

Pattern recognition against polarized red noise

flux and angle

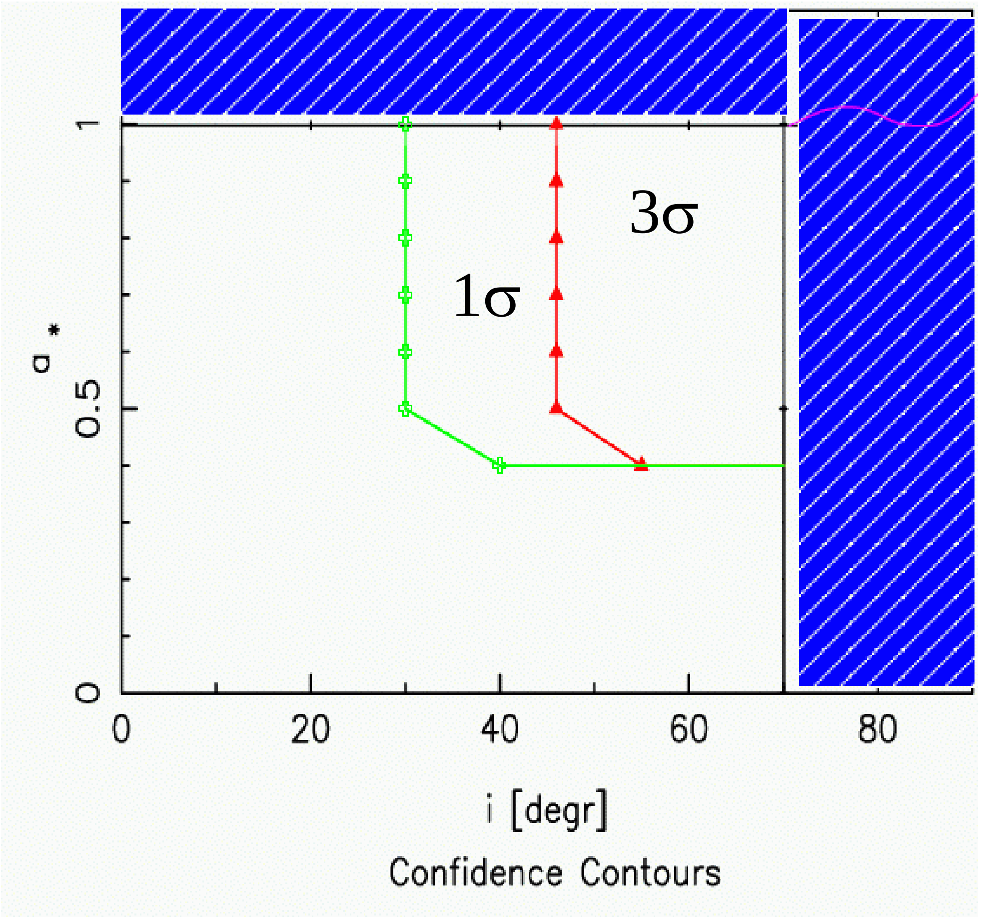
flux and degree



Polarized flares as the signature of strong gravity are significant against randomly polarized red noise

Polarization data are consistent with the orbiting spot hypothesis

NIR Polarized Flux Density from SgrA*



χ^2 analysis indicates
a= 0.4-1
i=50^o-70^o

Meyer, Eckart, Schödel, Duschl, Muzic, Dovciak, Karas 2006a
Meyer, Schödel, Eckart, Karas, Dovciak, Duschl 2006b
Eckart, Schödel, Meyer, Ott, Trippe, Genzel 2006

~4min prograde
~30min static
~60min retrograde
for 3.6x10**6Msol

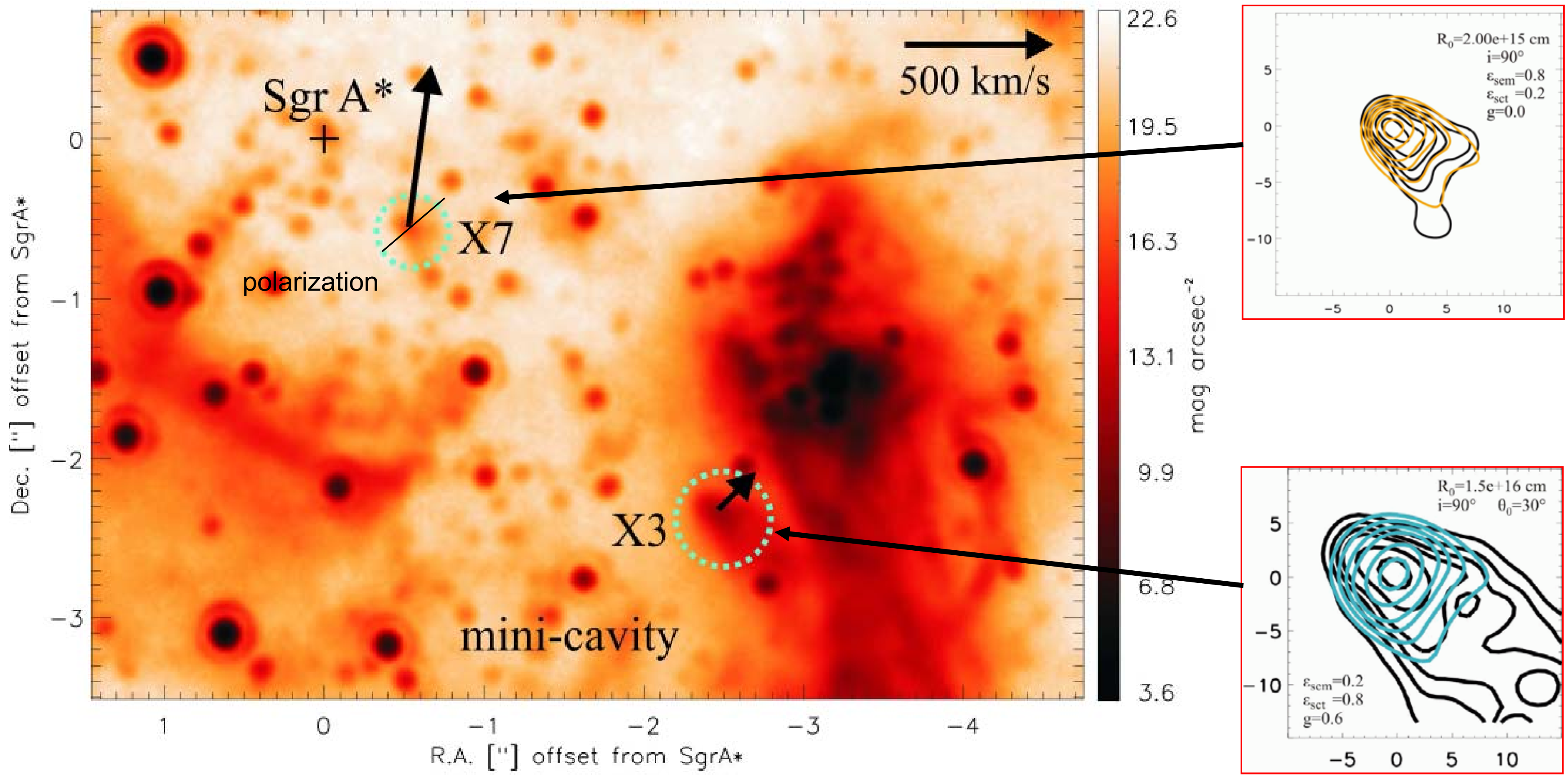
QPOs as repeatedly occurring signature of strong gravity in a spotted disk with sveral spots brightest close to the ISCO?

What is the power distribution in sub-mm wavelength light curves?

The SMBH Interacting with the GC ISM

The inefficient inflow of matter i.e. the accretion as a function of radius – must result in an outflow from the immediate vicinity of the SMBH

Cometary Sources: Shaped by a Wind from SgrA*?

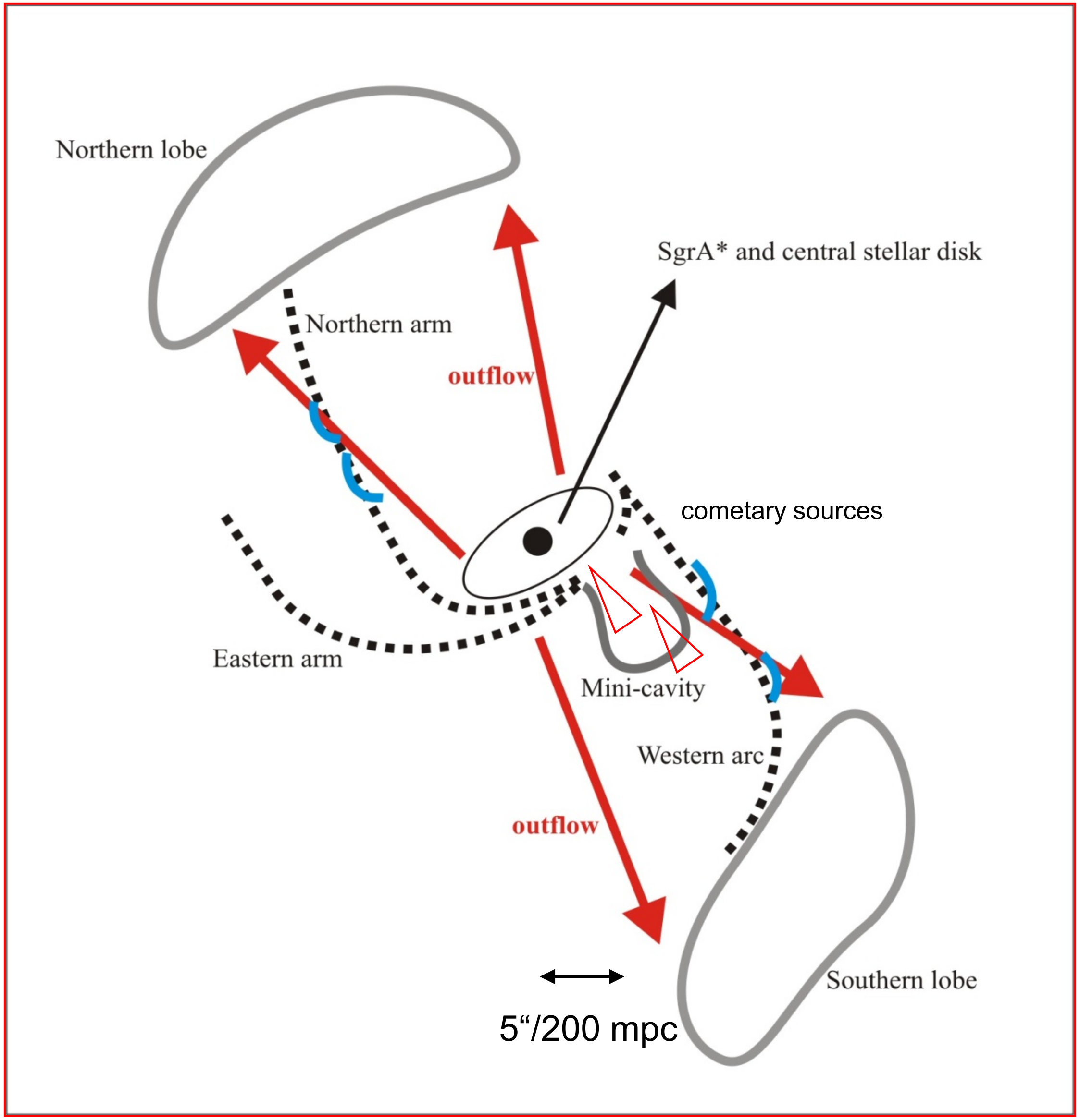


X7 polarized with 30% at PA -34+-10
Mie → bow-shock symmetry along PA 56+-10
includes direction towards SgrA*

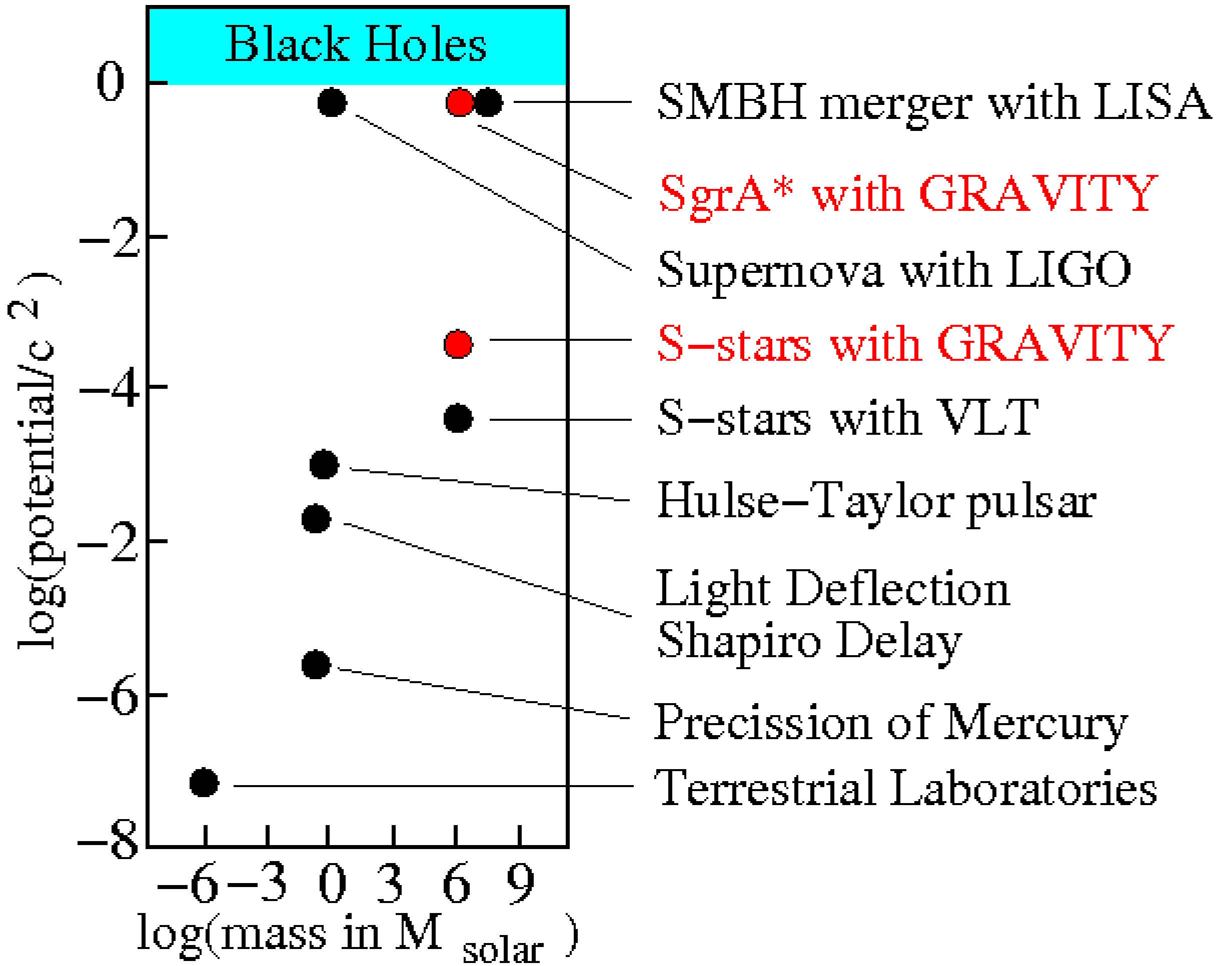
Besides the Mini-Cavity – the strongest indication for a fast wind from SgrA*!

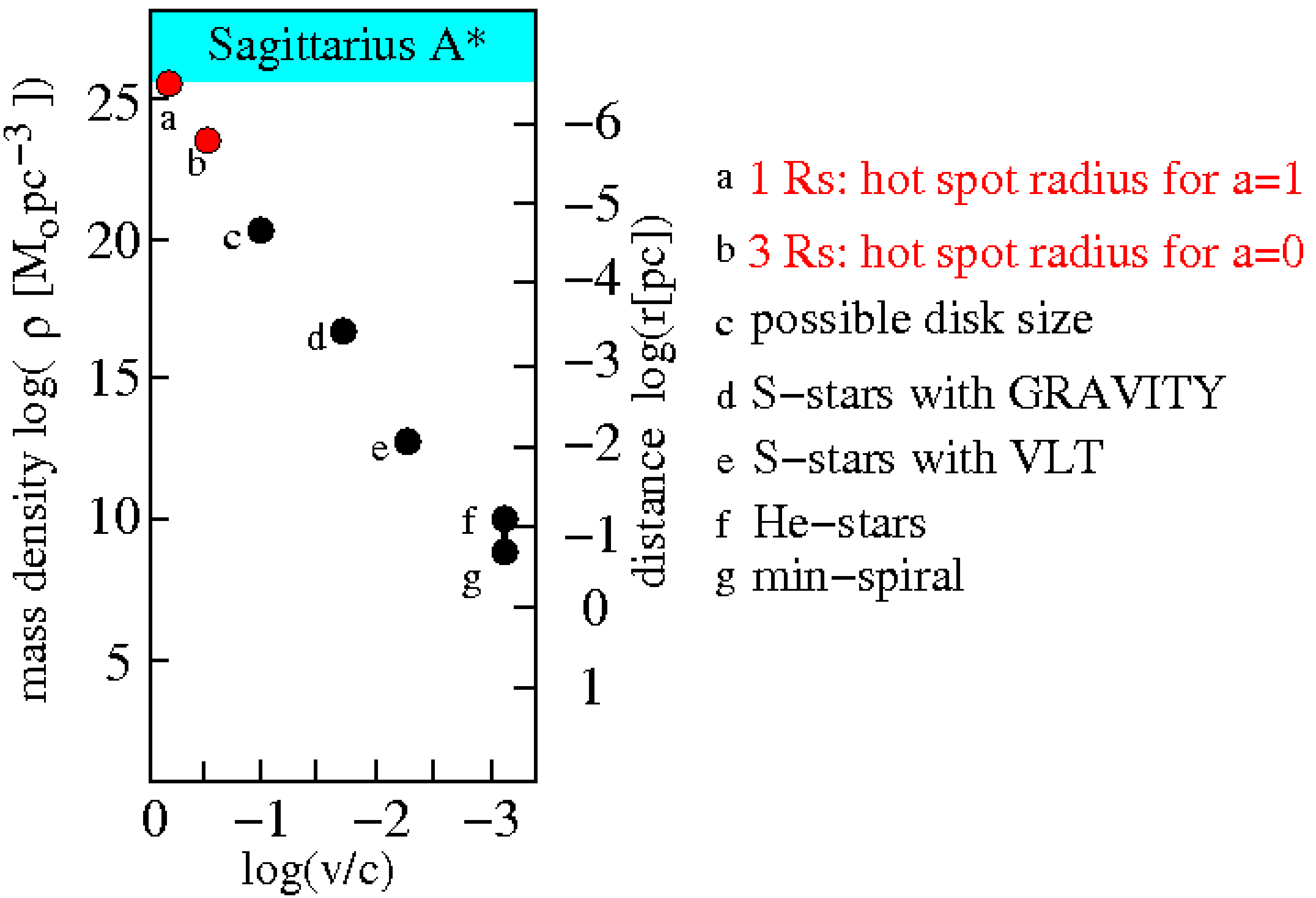
Muzic,Eckart, Schödel et al. 2007, 2009

Sketch of an Outflow Model: The Combined Wind from the Cluster of Hot Stars and SgrA*



Muzic, Eckart, Schödel et al. 2007
A&A 469, 993
Sabha, Eckart, Witzel, et al. 2009


Black Holes
0
−2
−4
−2
−6
−8
log(potential/c 2)
−6 −3 0 3 6 9
log(mass in M solar)
SMBH merger with LISA
SgrA* with GRAVITY
Supernova with LIGO
S−stars with GRAVITY
S−stars with VLT
Hulse−Taylor pulsar
Light Deflection
Shapiro Delay
Precission of Mercury
Terrestrial Laboratories



Sagittarius A*
mass density log(ρ [M$_o$pc^{-3}])
25
20
15
10
5
a
b
c
d
e
f
g
0
−1
−2
−3
log(v/c)
−6
−5
−4
−3
−2
−1
0
1
distance log(r[pc])
a 1 Rs: hot spot radius for a=1
b 3 Rs: hot spot radius for a=0
c possible disk size
d S−stars with GRAVITY
e S−stars with VLT
f He−stars
g min−spiral

No alternatives to the

Black Hole?!

Neutrino Ball Scenario

supported by degeneracy pressure

Scaling relation between mass and radius (Munyaneza, Tsiklauri,& Viollier 1999):

$$MR^3 = \frac{91.869\hbar^6}{G^3 m_\nu^8}\left(\frac{2}{g_\nu}\right)^2$$

$$MR^3 = 3\times10^6 (23.18mpc)^3 \left(\frac{17.2keV}{m_\nu c^2}\right)^8 g_\nu^{-2}$$

For large neutrino masses small radii can be obtained.
However, to explain all nuclear dark masses ranging between 3 million (GC) and 3000 Million (M87) solar masses the
putative, as yet unidentified neutrinos
must have a mass in the range of 17keV.
Radii for the GC are then of the order of 15mpc

Can be excluded for the Galactic Center !

Boson Star Scenario

Torres, Capozziello & Lambiase 2000, Phys.Rev 62, 104012
supported by Heisenberg uncertainty principle

non-interaction Bosons:
Kaup 1968, Ruffini & Bonazzola 1969

$$m = 1 GeV, R = 1 fm, M = 10^{-19} M_o$$

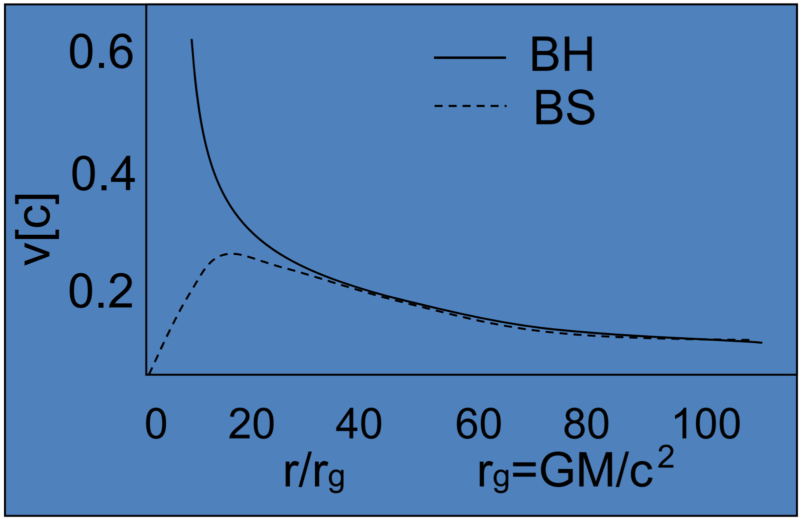
self-interacting Bosons:
Colpi, Shapiro & Wasserman 1986, Torres, Capozziello & Lambiase 2000, Lu & Torres 2003:

For a large range of hypothetical boson masses much larger total masses within radii of only several times their Schwarzschild radii are possible.

$$M[10^6] \approx M(x) / m[GeV] \times 10^{-25}$$

$$x = mr, m \approx 3 \times 10^{-26} GeV$$

$$r[pc] \approx x / m[GeV] 7 \times 10^{-33}$$

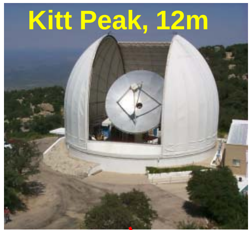


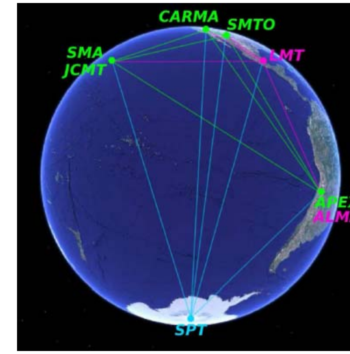
Unlikely to form a stabile configuration at the Galactic Center !

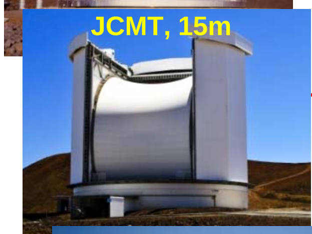
Synergies

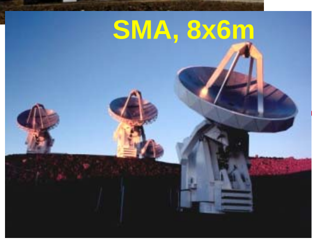
- JWST
- VLBI, ALMA, SKA
- Infrared interferometry

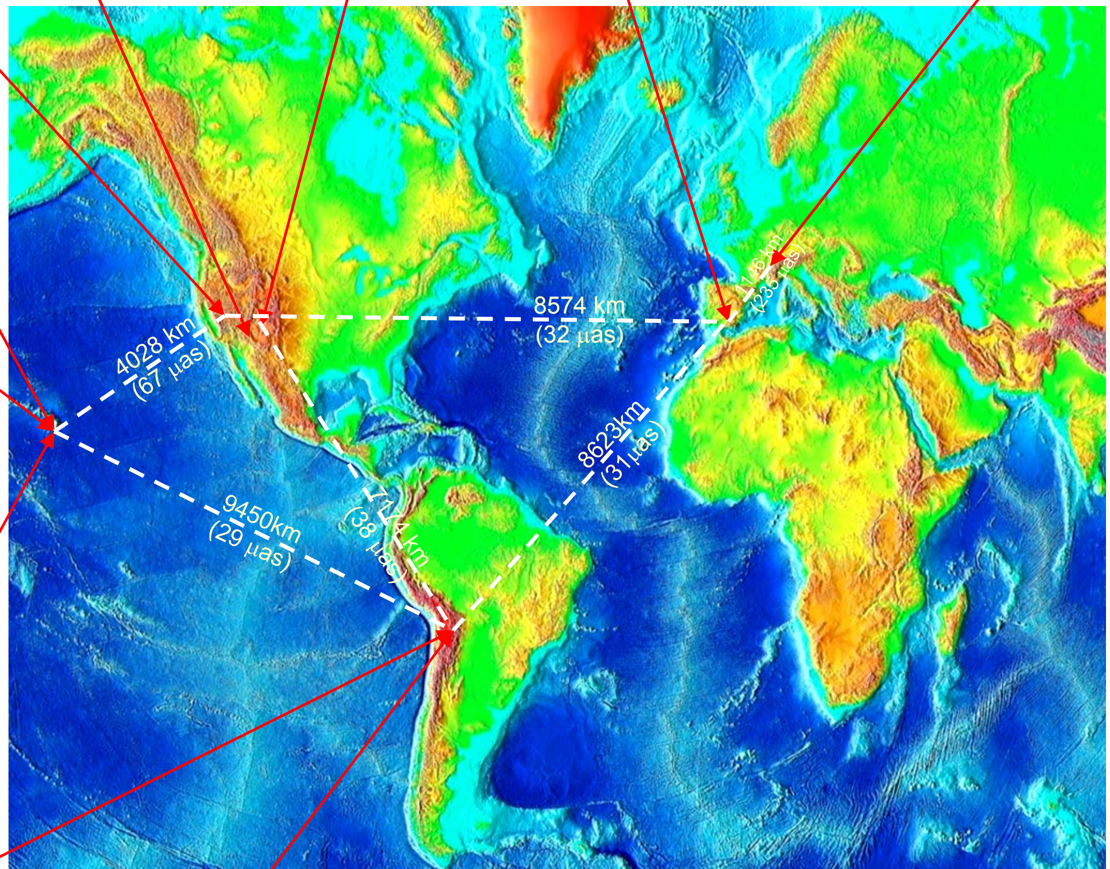
Preparing for new NIR Measurments







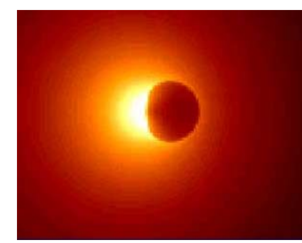


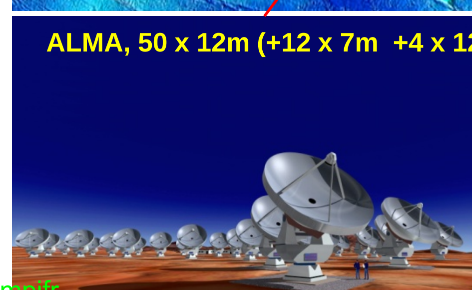


Angular Resolution:

25-30 µas @230 GH

16-20 µas @345 GH





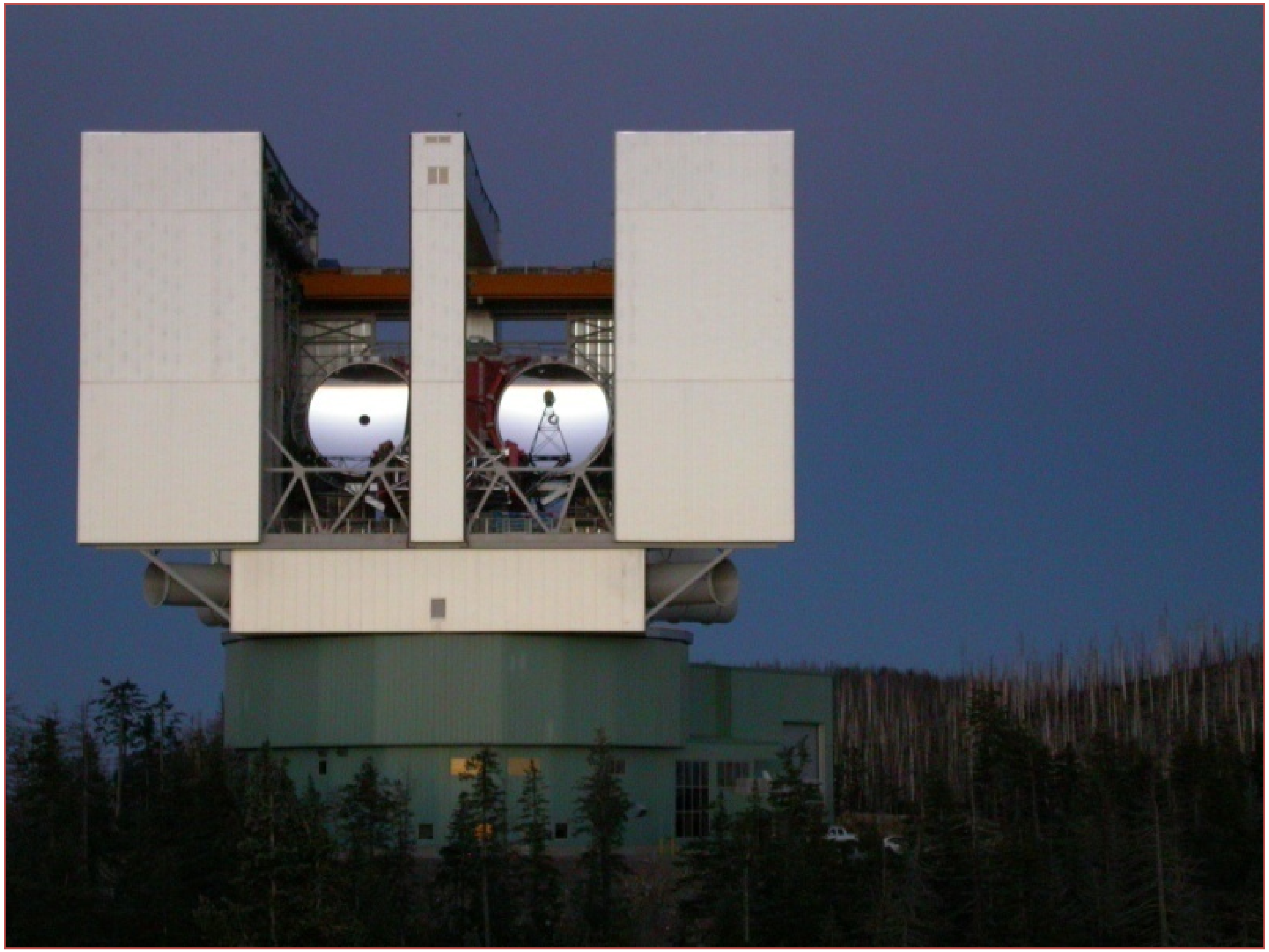
(angular resolutions calculated for 230 GHz)

Imaging Black Holes with global mm-/sub-mm VLBI

("Event Horizon Telescope")

composition: Krichbaum@mpifr

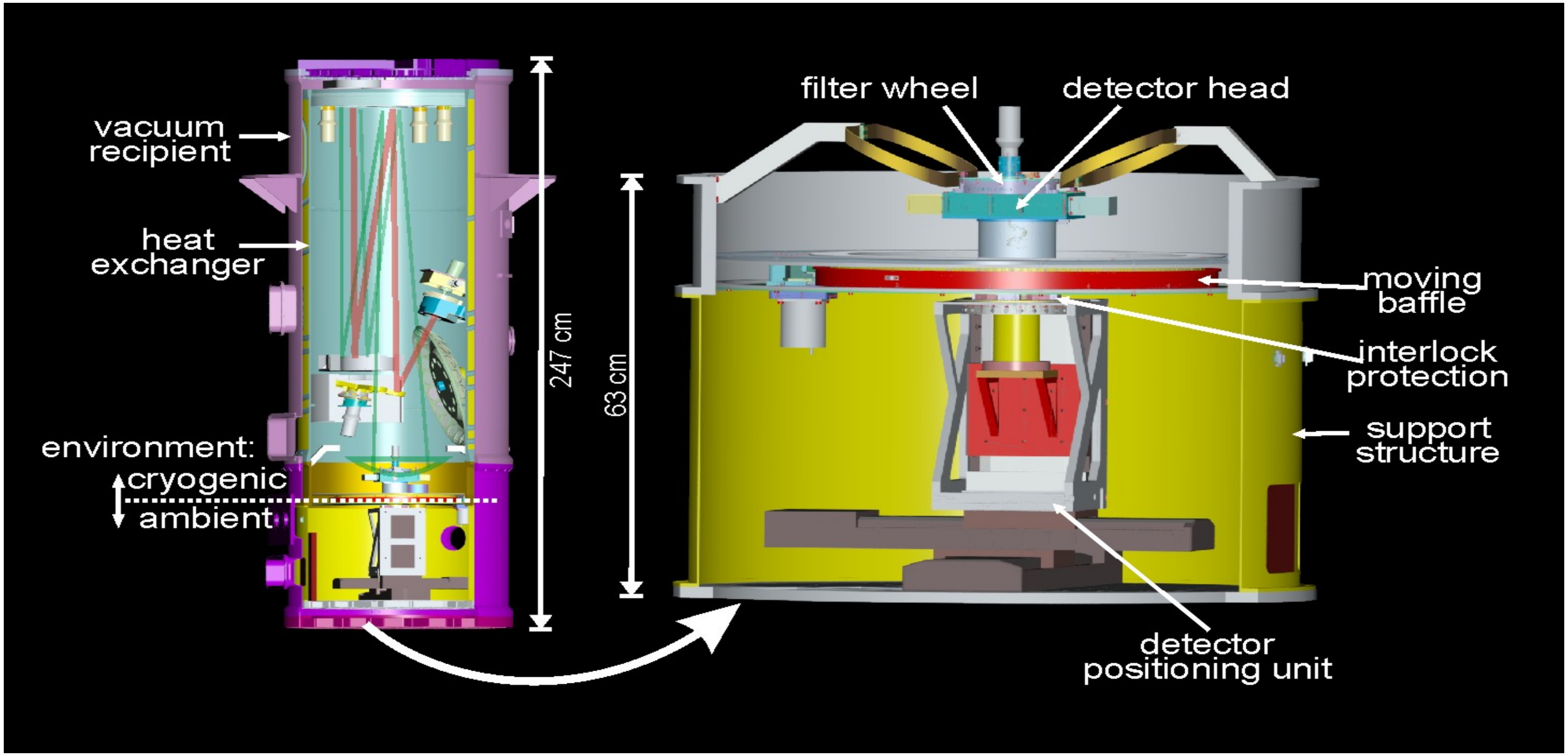
LBT: LINC-NIRVANA



MPIA Heidelber
Arcetri Florence
Uni of Cologne,
MPIfR Bonn

Large
Bincular
Telscope
in Arizona
2x8.4m Spiegel

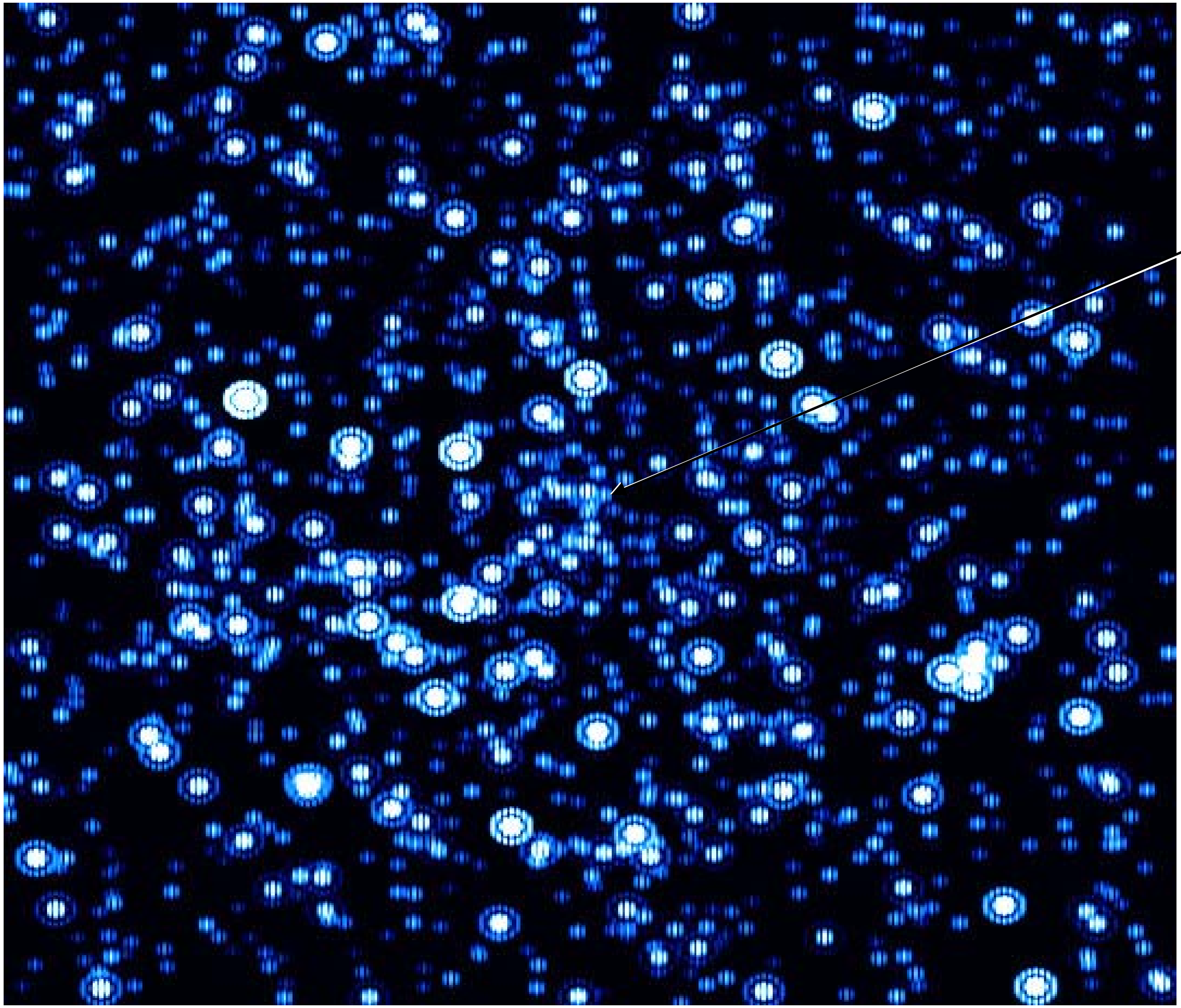
LBT: LINC-NIRVANA



Straubmeier, Bertram, Zuther, Eckart

Cologne provides: Dew
FFTS, and cooling syste

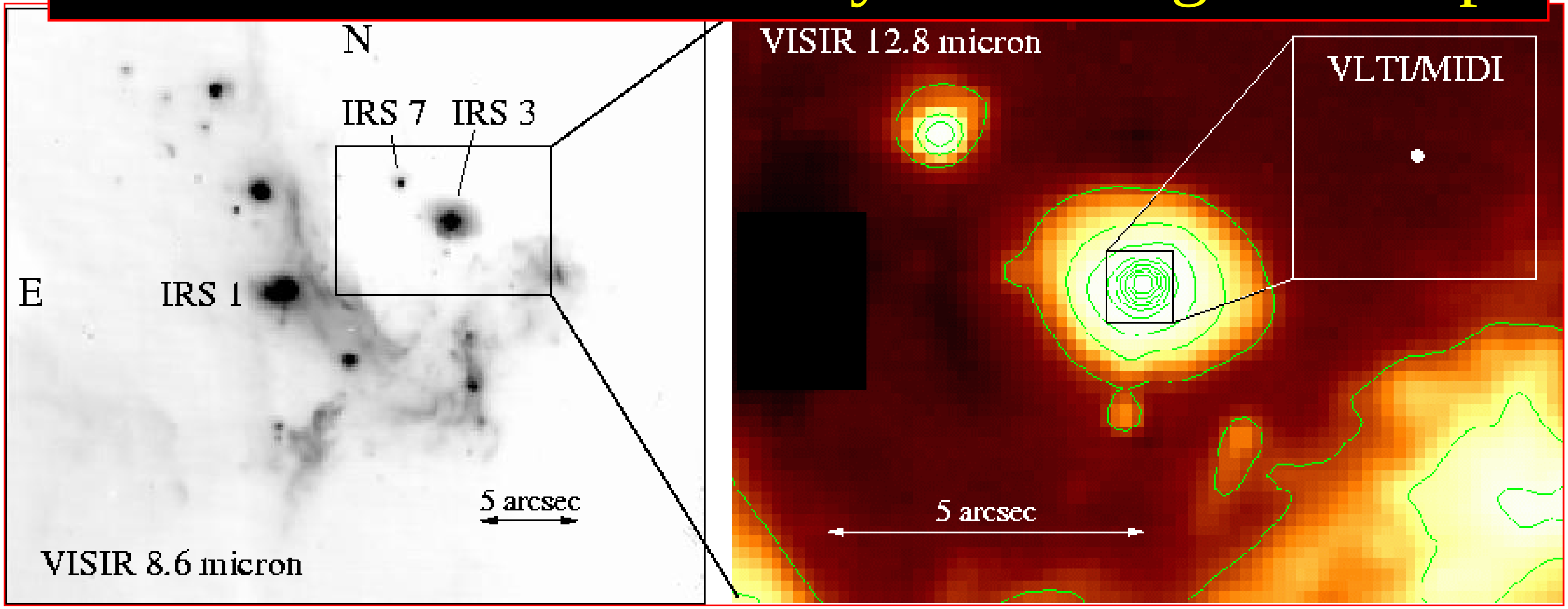
LBT: LINC/NIRVANA



~10x10 arcsec
~0.5x0.5 pc

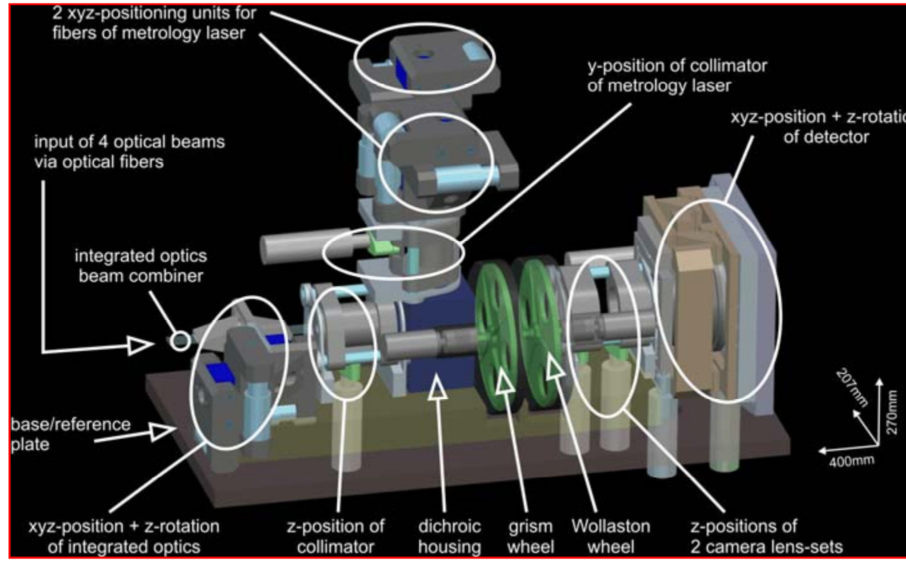
The Galactic Center with the LBT

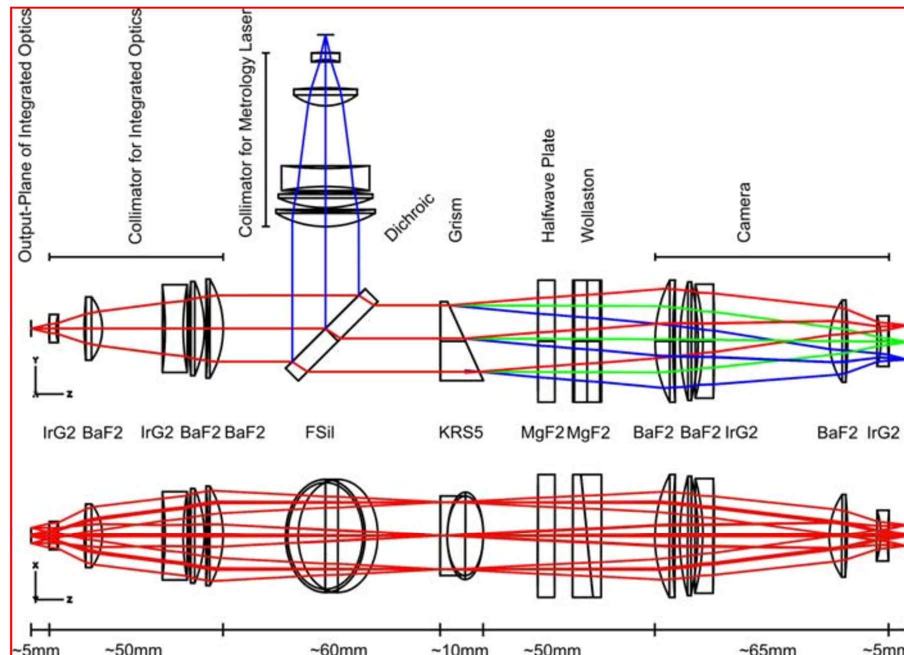
First VLTI Measurements on the stars IRS7 and IRS3 in the Galactic Center by the Cologne Group



IRS3 and IRS7:
Pott, Eckart, Glindemann, et al., 2008, A&A 487, 413
Pott, Eckart, Glindemann, et al., 2008, A&A 480, 115

VLTI: GRAVITY





MPE, Garching

MPIA, Heidelberg

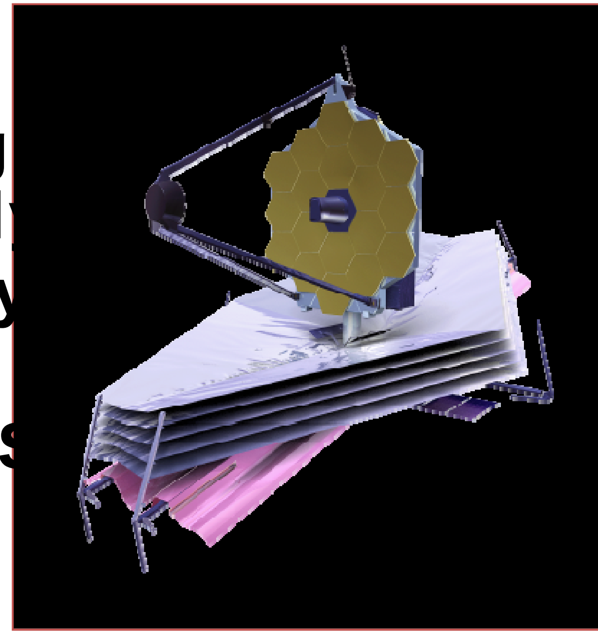
Observatoire Paris-Medon

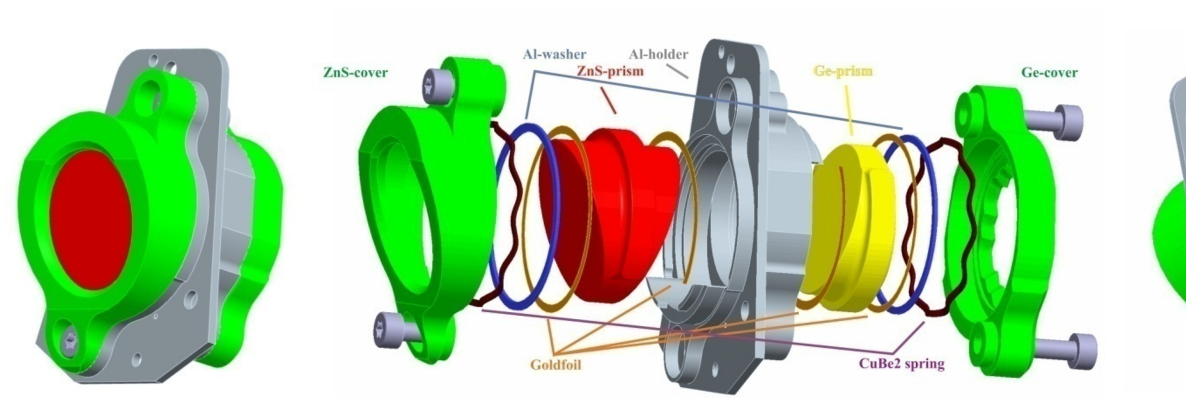
Cologne University

MIRI / JWST

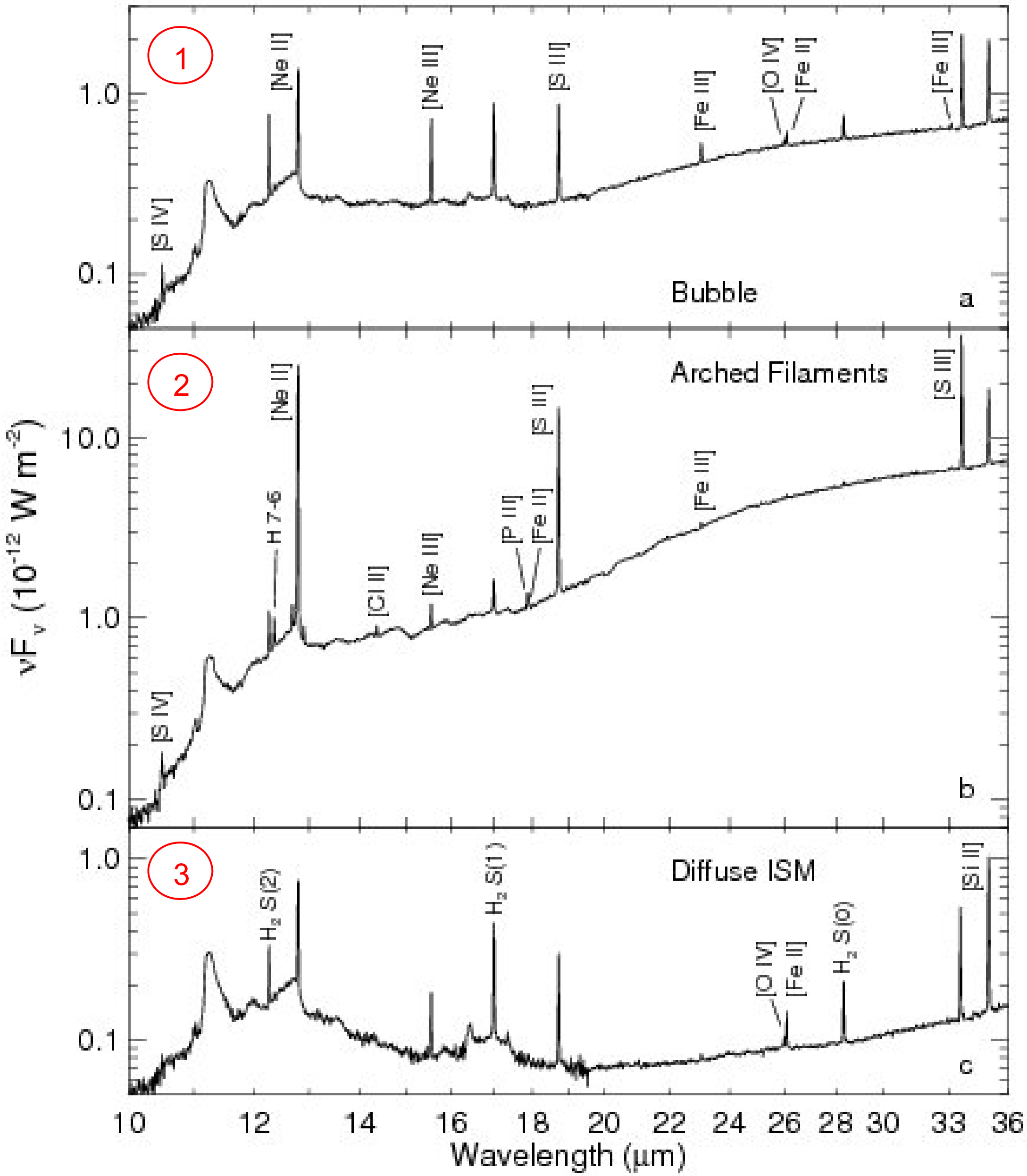
MIRI JWST
Consortium
G. Wright Edinburg

Cologne is the only
German University
Institute that
contributes to JWS

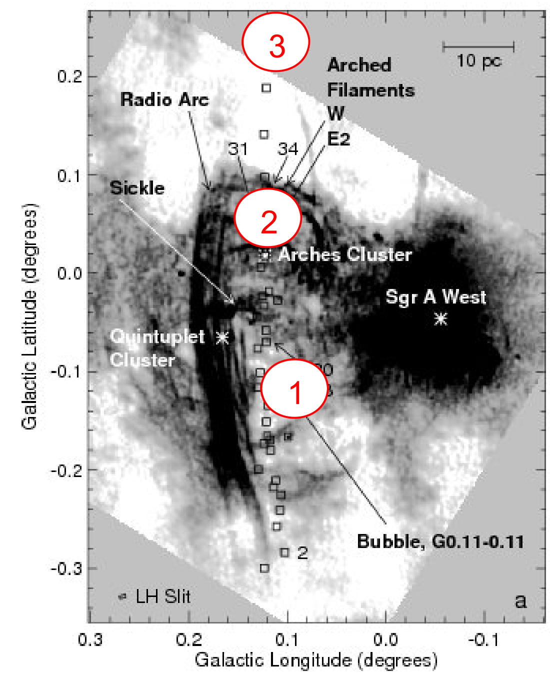




Spectroscopic probes



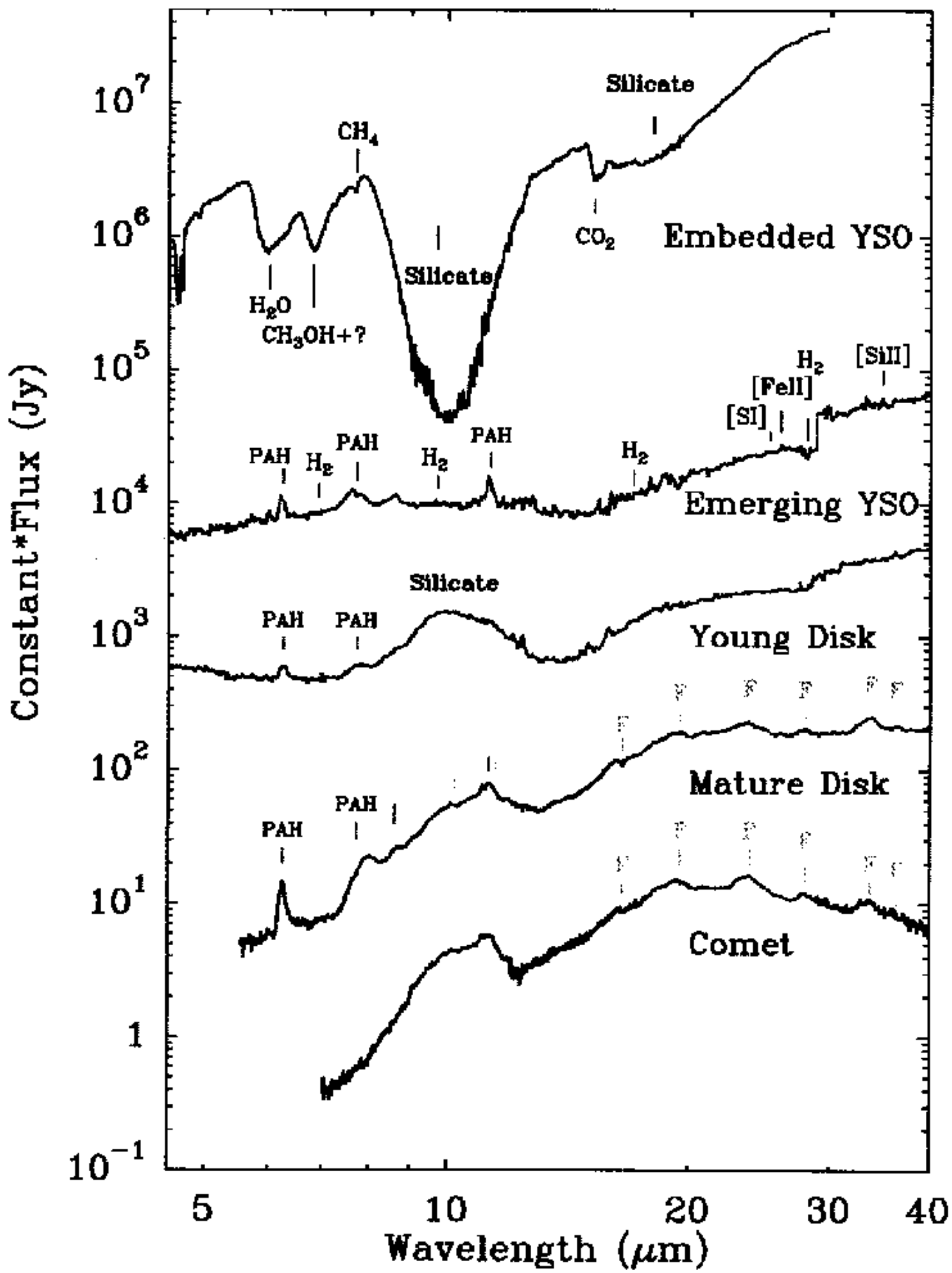
SPITZER spectra towards two characteristic regions in the Galactic Center
Simpson et al. 2007



Spectroscopic probes

One strength of the MIRI IFUs: Full spectral coverage!

Both spectroscopic and overall SED properties of target sources will allow us to identify and classify young stars and disks.



ISO SWS MIR spectra of young stars and circum-stellar disks at different stages of their evolution
Malfait et al. 1998; Gibb et al. 2000, Ancker et al. 2000a,b, Crovisier et al. 1997

Spectroscopic probes

NH_3 (9um), CH_3OH (9.7um C-0 stretching) features
5.5-7.5 H_2O ice features as reported by
Boogert et al. 2008 (Spitzer) and Bottinelli et al. 2008

Shocked gas in arcs, bow shocks and interaction zones
could be observed in emission through lines from
neutral molecular and atomic hydrogen species
H_2 S(0), S(1), S(2) @ 28.2, 17.0, 12.3 um
HI 7-6 @ 12.37 um

and fine structure lines from ionized species
[Ne II] 12.8 um, [Ne III] 15.55 um, [S IV] 10.51 um, [CII] 14.37 um
with ionization potentials between 20 and 40 eV
(e.g. Simpson et al. 2007 using Spitzer)

Arched shocked features and PDR regions will also show strong
6 and 8um PAH emission (Archers/Spitzer Cotera et al. 2006)

MIRI JWST targeting the Galactic Center

The central pointing contains some of the most exciting sources at the Galactic Center !

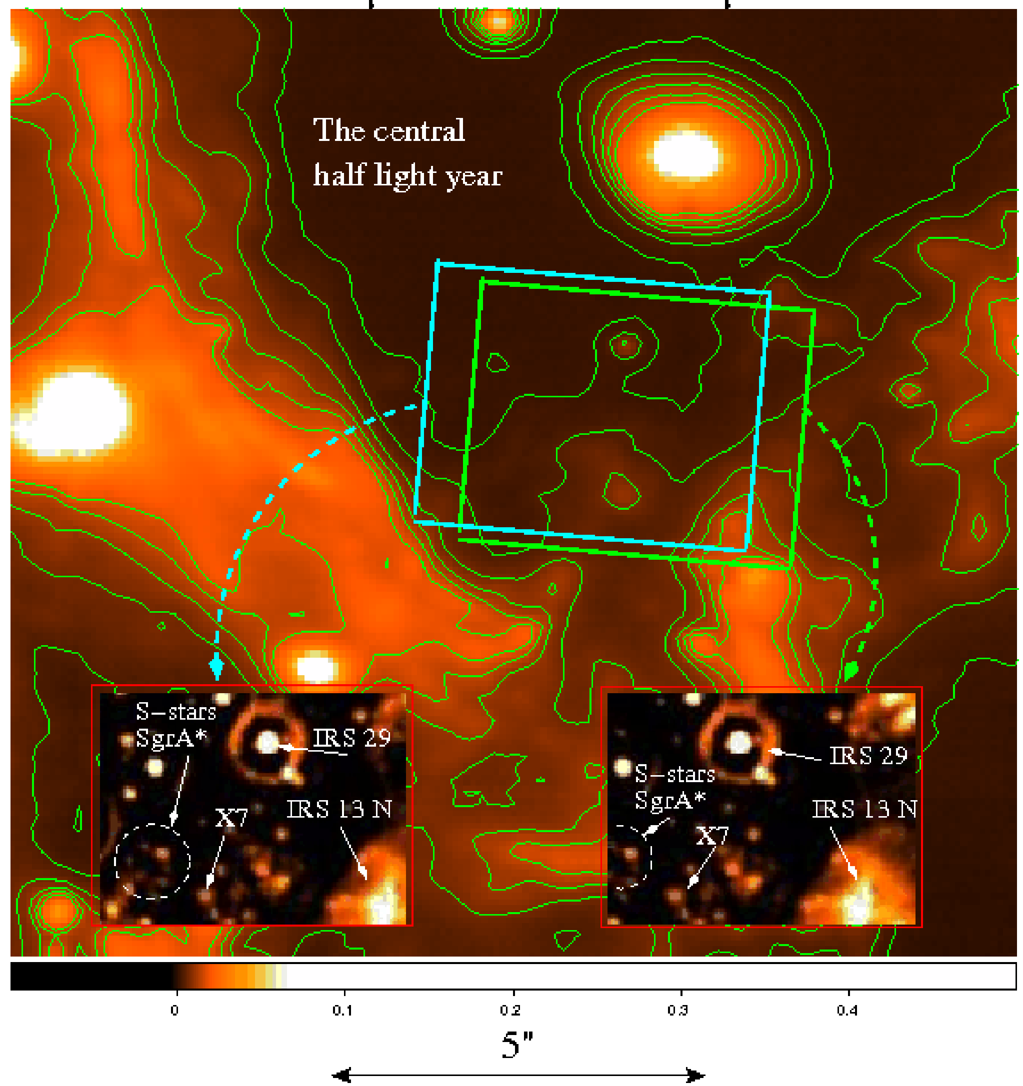
Both the
5.0 – 7.7 μm and the
7.7 – 11.9 μm IFUs
can be placed comfortably
between the bright GC stars
without violating the upper
sensitivity limits of the array.

8.6 μm VISIR image
(Schödel, Eckart et al. 2007).
angular resolution 0.25”

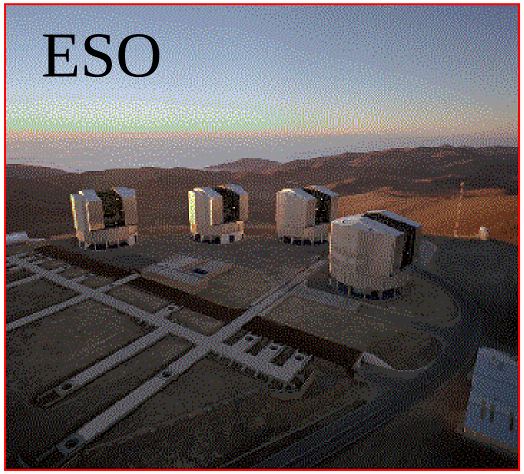
Flux of IRS29 ~200 mJy

LIMIT 500 mJy
~0.1’’ pointing accuracy
targeting within 30’’

5.0–7.7 μm and 7.7–11.9 μm IFU



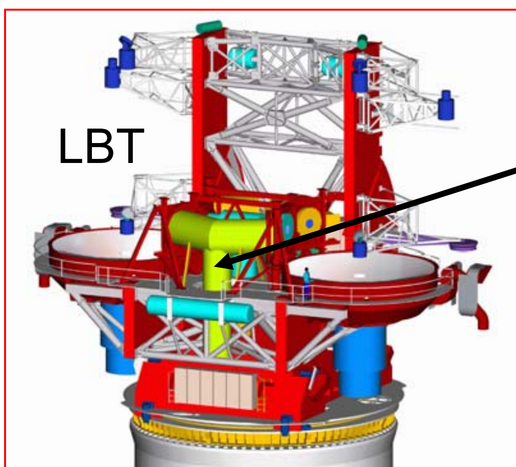
ESO E-ELT



NL lead Euro-Team
University of Cologne
participation
METIS @ E-ELT

MPE, MPIA, Paris
Universitity of Cologne
participation
GRAVITY @ VLTI

The Galactic Center is a unique laboratory in which one can study physics in the vicinity of large masses



NIR/OPT Beam Combiner:
Universitity of Cologne
MPIA, Heidelberg
Osservatorio Astrofisico di Arcetri
MPIfR Bonn

JWST

Cologne
contribution to
MIRI on JWST