The Galactic Center Black Hole and its Environment

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SEVENTH FRAMEWORK PROGRAMME

STRONGGRAVITY

EU FP7-SPACE research project 312789 2013 - 2017

Max-Planck-Institut für Radioastronomie

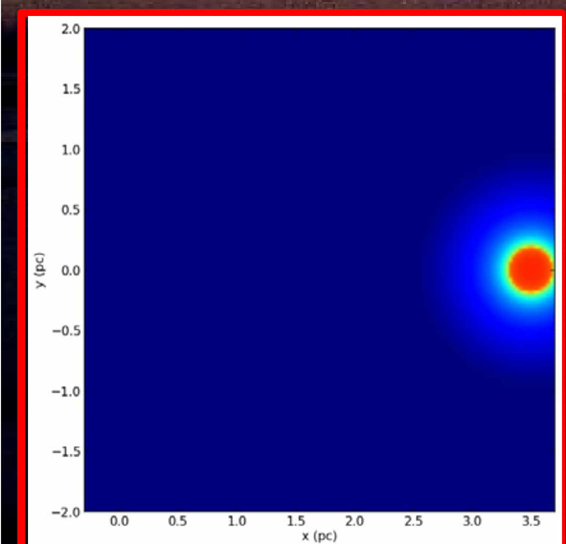
I. Physikalisches Institut Universität zu Köln

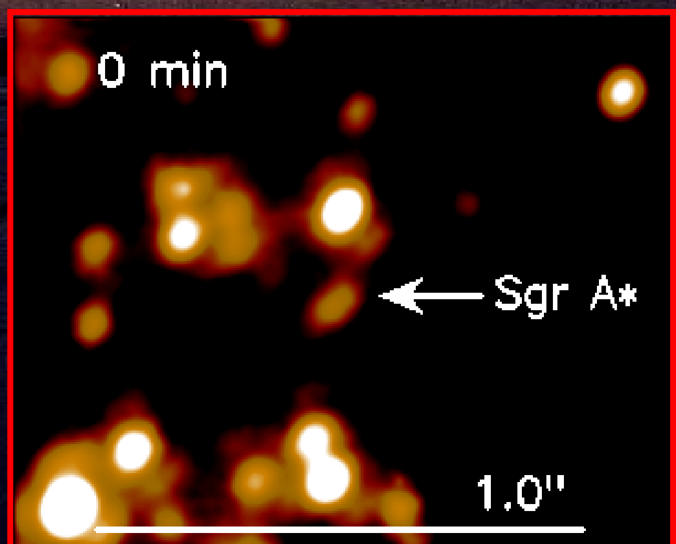
Extreme-Astrophysics in an Ever-Changing Universe

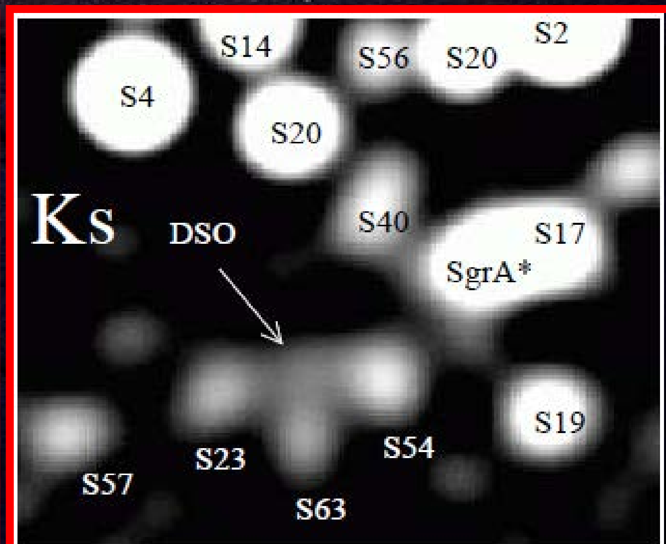
Time-Domain Astronomy in the 21st Century

Celebrating Prof. J. H. Seiradakis' 40-yr Career

16-20 June 2014 Ierapetra, Crete

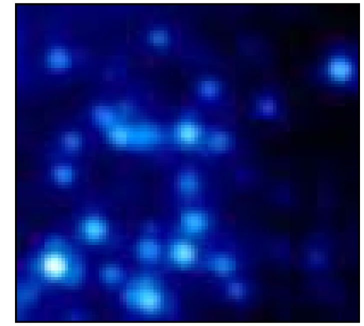




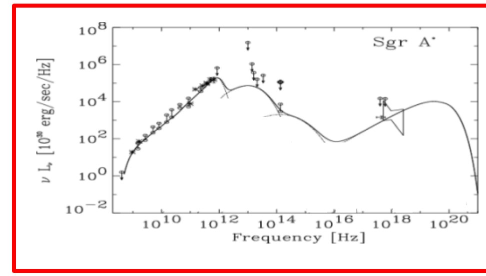


•Introduction

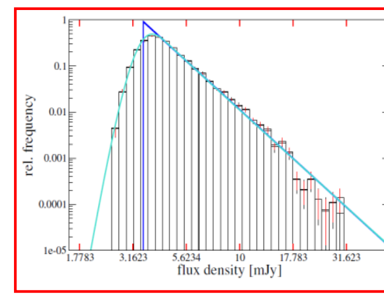
- The SMBH SgrA* and its environment



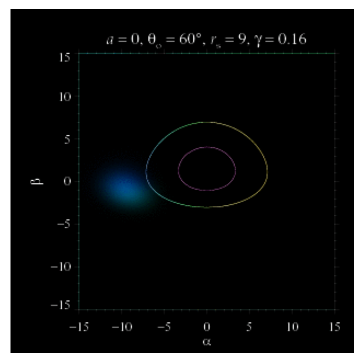
- Synchrotron and synchrotron self-Compton modeling the NIR/X-ray flares of SgrA*



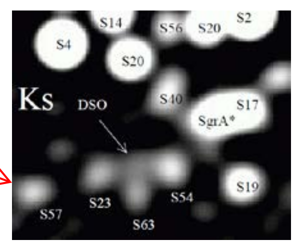
- Statistics of NIR light curves of SgrA*



- Polarization signatures
  Relativistic disk calculations



- Upcoming violent events

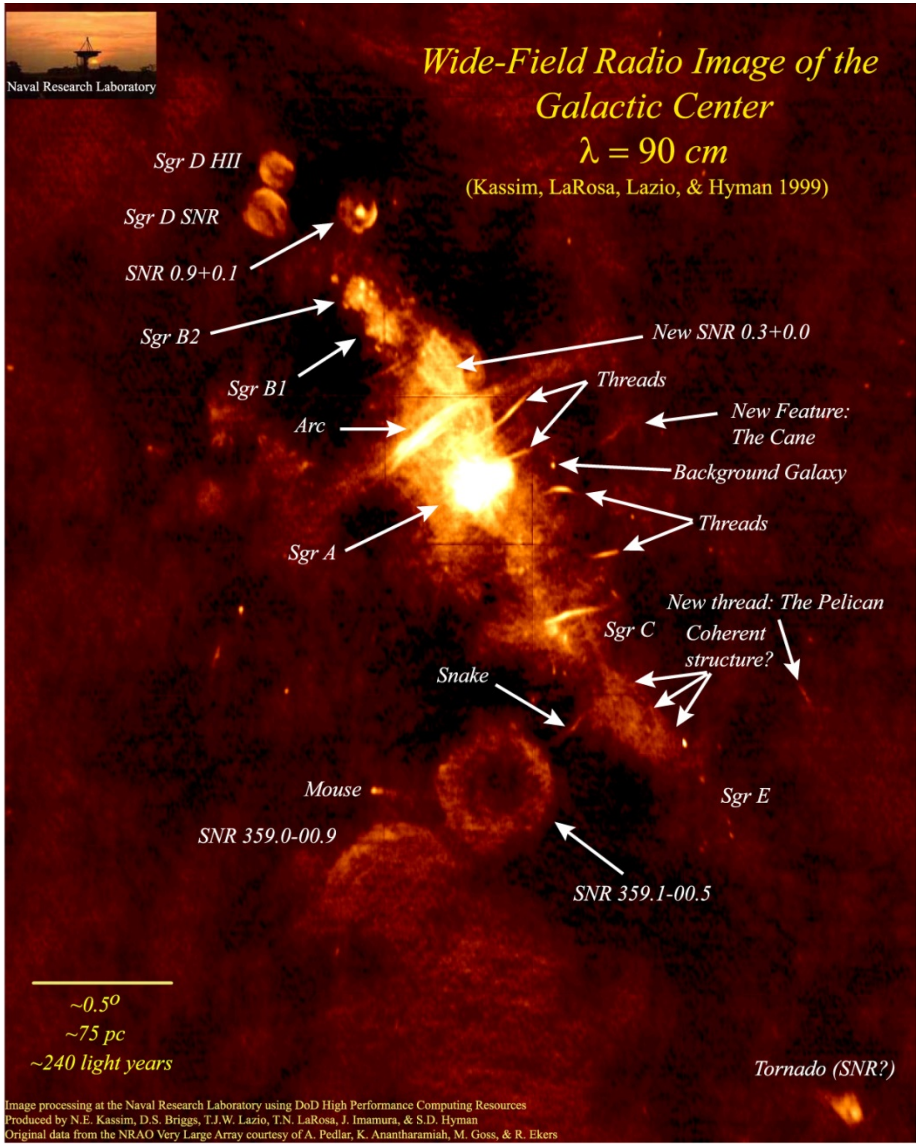


•Summary

Flares: positive flux density excursions in NIR and excursions above the quiescent state in X-ray

The Center of the Milky Way

Closest galactic genter at 8 kpc
High extinction of Av=30 Ak=3
Stars can only be seen in the NIR



VLA 90cm

Kassim, Briggs, Lasio, LaRosa, Imamura, Hyman

The Evironment of SgrA*

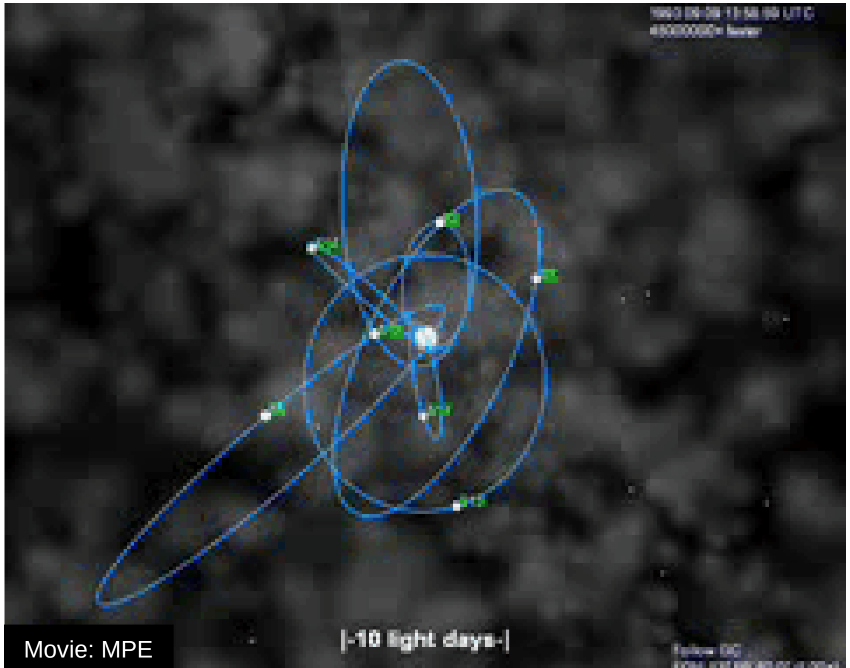
Orbital motion of high-velocity S-stars

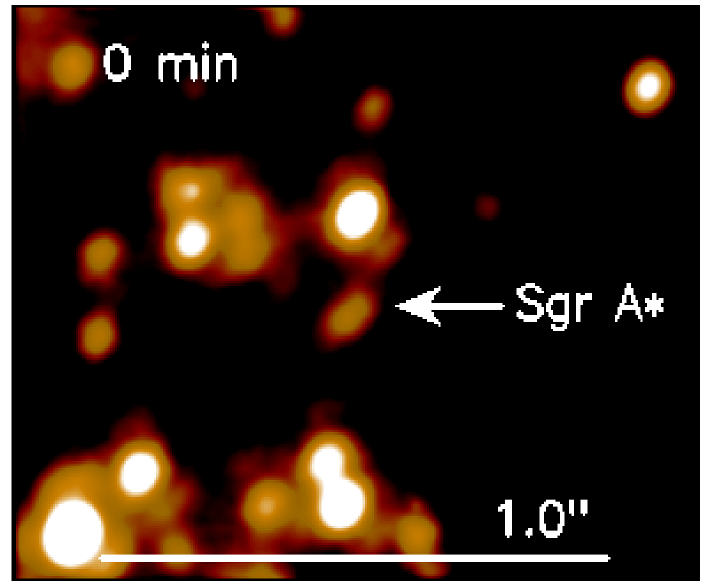
On the possibility to detect relativistic and Newtonian peri-center shifts

- Granularity of scatterers
- Search for stellar probes

SgrA* and its Environment

Orbits of High Velocity Stars
in the Central Arcsecond

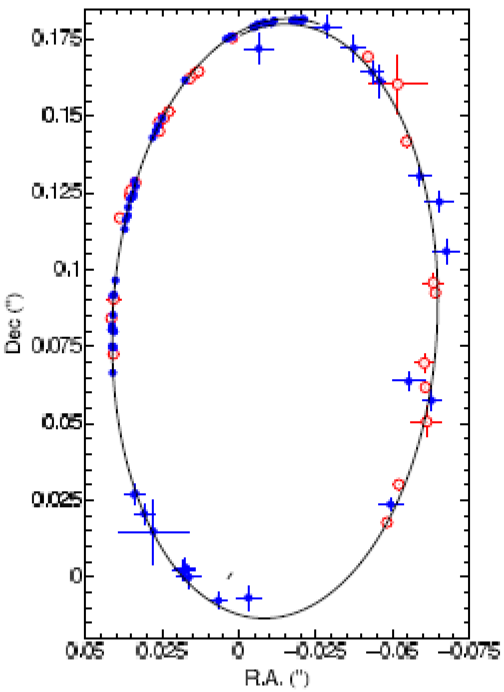


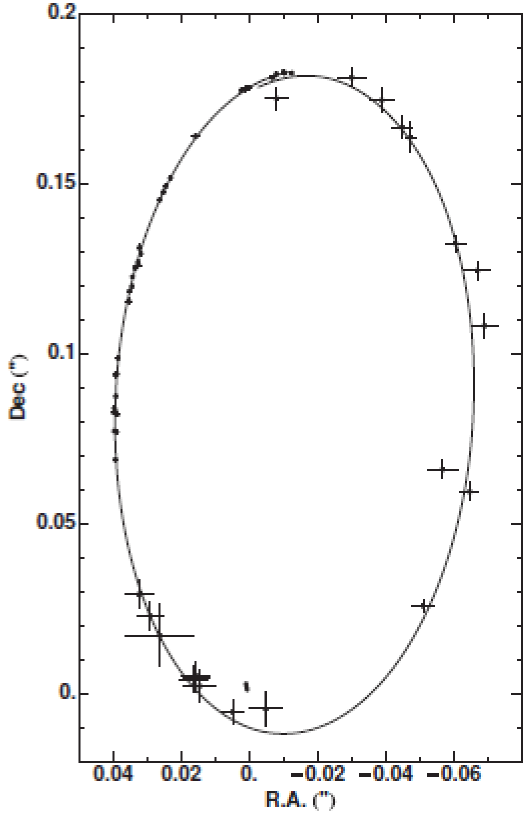


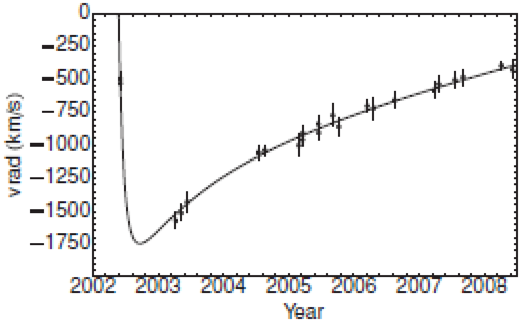
Eckart & Genzel 1996/1997 (first proper motions)
Eckart+2002 (S2 is bound; first elements)
Schödel+ 2002, 2003 (first detailed elements)
Ghez+ 2003 (detailed elements)
Eisenhauer+ 2005, Gillessen+ 2009
(improving orbital elements)
Rubilar & Eckart 2001, Sabha+ 2012, Zucker+2006
(exploring the relativistic character of orbits)

~4 million solar masses
at a distance of
~8+-0.3 kpc

Progress in measuring the orbits







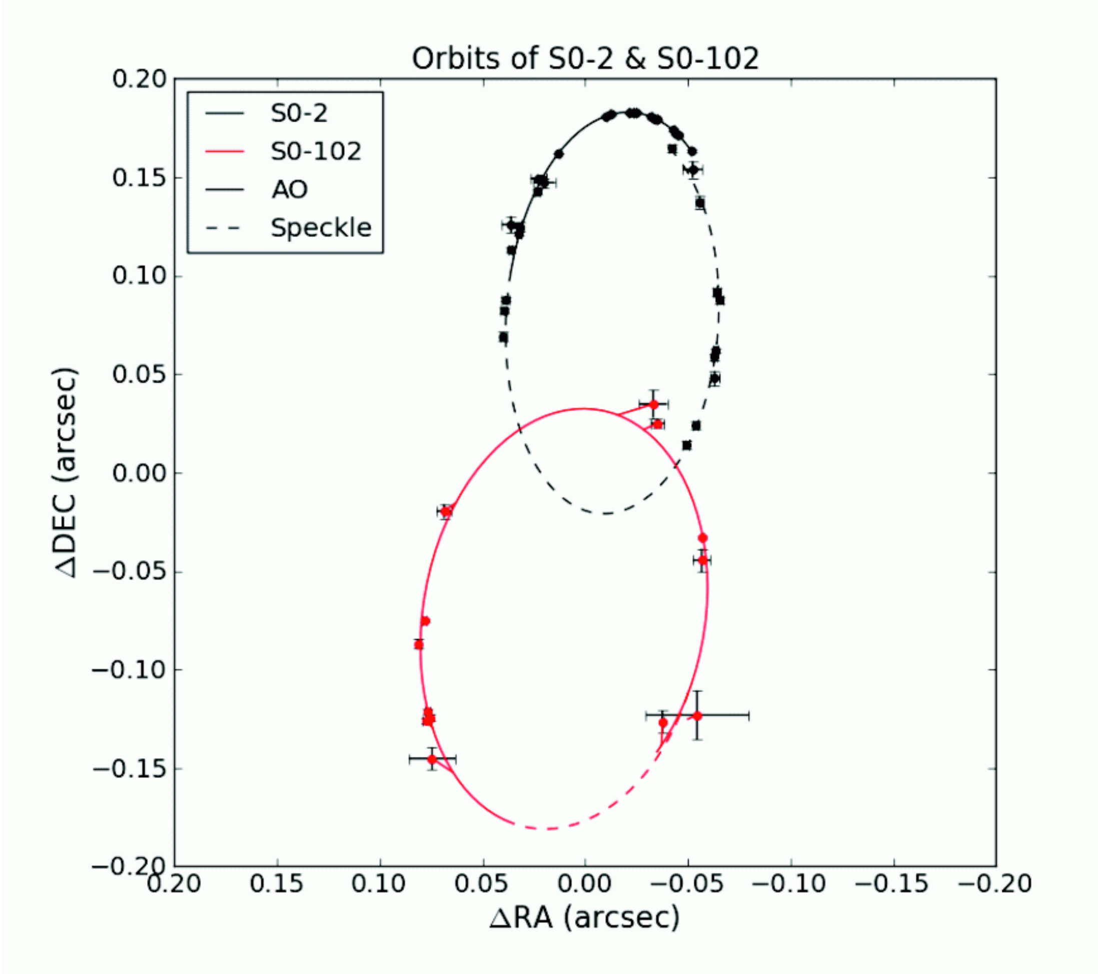
$$T_{orbit} = 15.6 \pm 0.4 yrs$$

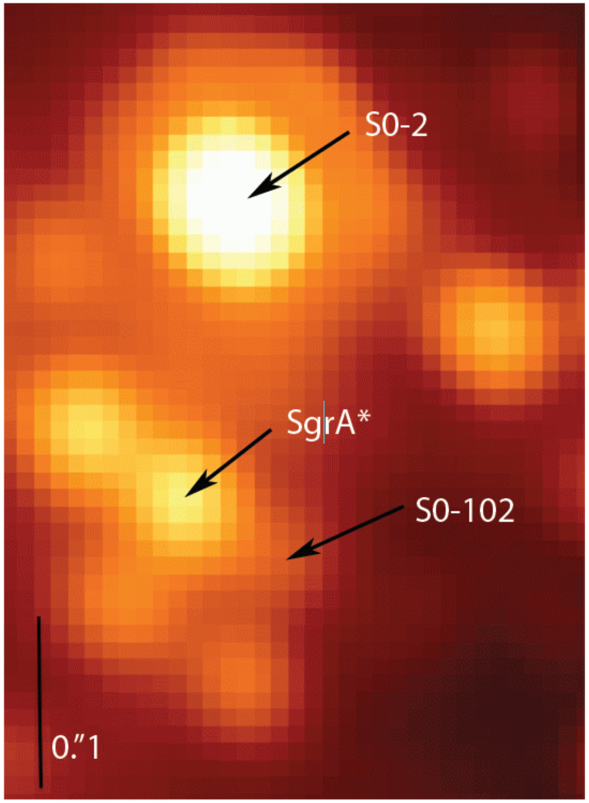
$$e = 0.883 \pm 0.003$$

$$a = 0.125 \pm 0.002$$

Gillessen+ 2009

Shortest known period star





Shortest known period star with 11.5 years available to resolve degeneracies in the parameters describing the central gravitational potential (e=0.68) (Meyer et al. 2012 Sci 338, 84),

Bestimmung der Masse über S2

For S2 the 15 year orbit is closed. Using Kepler's laws we find

$$\boxed{M_{SgrA^*,S2} = \frac{4\pi^2}{G}\frac{a^3}{T^2}}$$

With the orbital time scale **T** and the long half axis **a.**

For S2 that results in::

$$\boxed{M_{SgrA^*} \approx (4 \pm 0.3) \times 10^6 M_o}$$

At the same time we can solve for the distance: 8+/-0.3 kpc

Eisenhauer et al. 2005

Histograms of the predicted peri-bothron change of S2 over one orbital period (~16 yr).

The shift due to relativity (~11′), has been subtracted. What remains is due to Newtonian perturbations (peri-bothron shift and pertrubation/scattering) from the field stars.

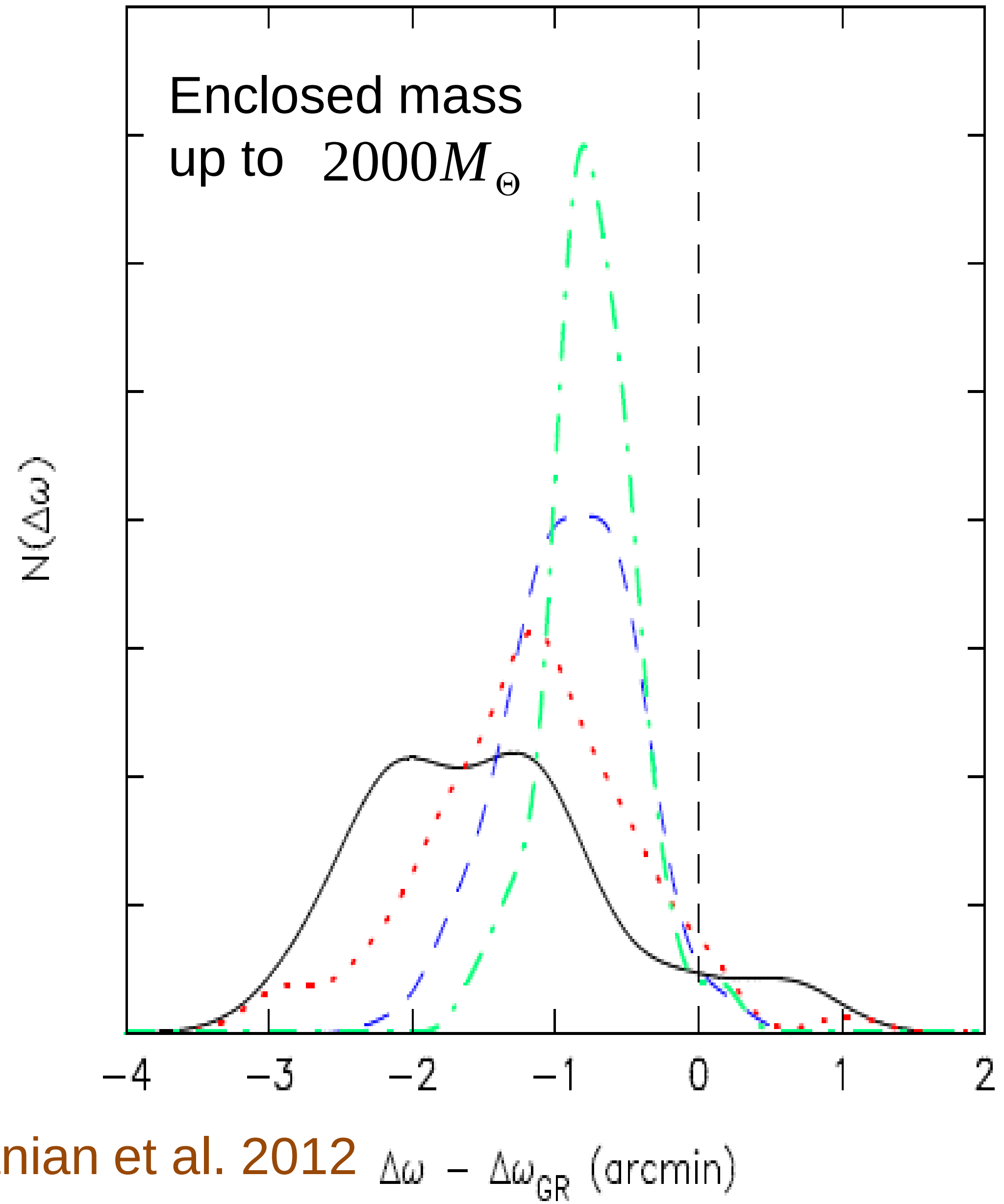
$$\frac{|\Delta \mathbf{L}|}{L_c} \approx K\sqrt{N}\frac{m}{M_\bullet}\frac{\Delta t}{P}$$

$$|\Delta e|_{\rm RR} \approx K_e\sqrt{N}\frac{m}{M_\bullet},$$

$$(\Delta\theta)_{\rm RR} \approx 2\pi K_t\sqrt{N}\frac{m}{M_\bullet}$$

Resonant relaxation:

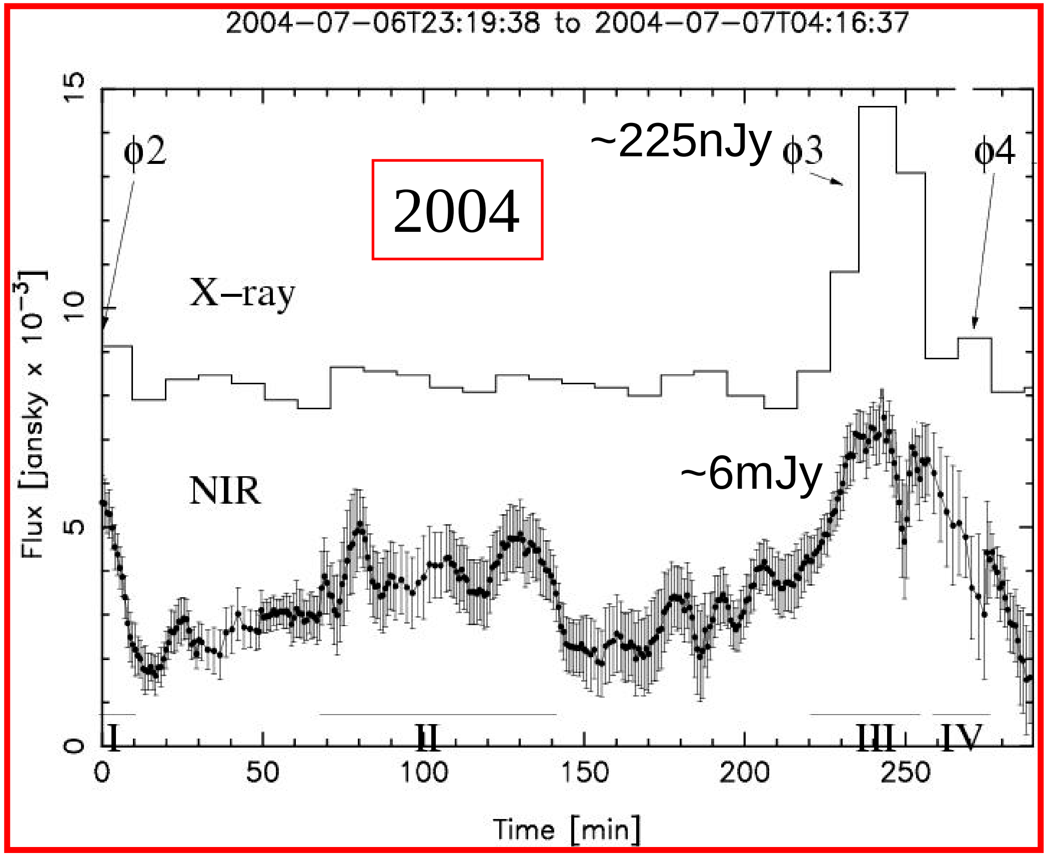
Rauch & Tremaine 1996
Hopeman & Alexander 2006
Merritt et al. 2010

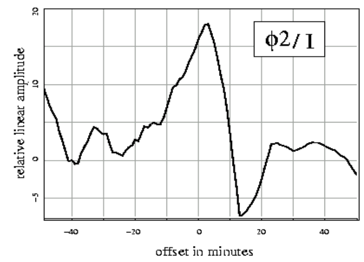


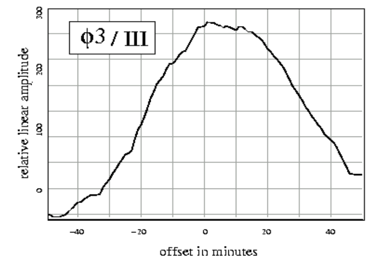
Sabha, Eckart, Merritt, Shahzamanian et al. 2012

Synchrotron and synchrotron self-Compton modeling the ***radio/NIR/X-ray*** flares of SgrA*

Simultaueous NIR/X-ray Flare emission 2004

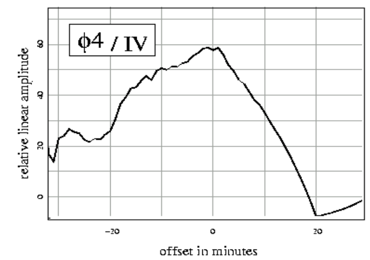






Time lags are less <10-15 minutes

NIR and X-ray flares are well correlated.

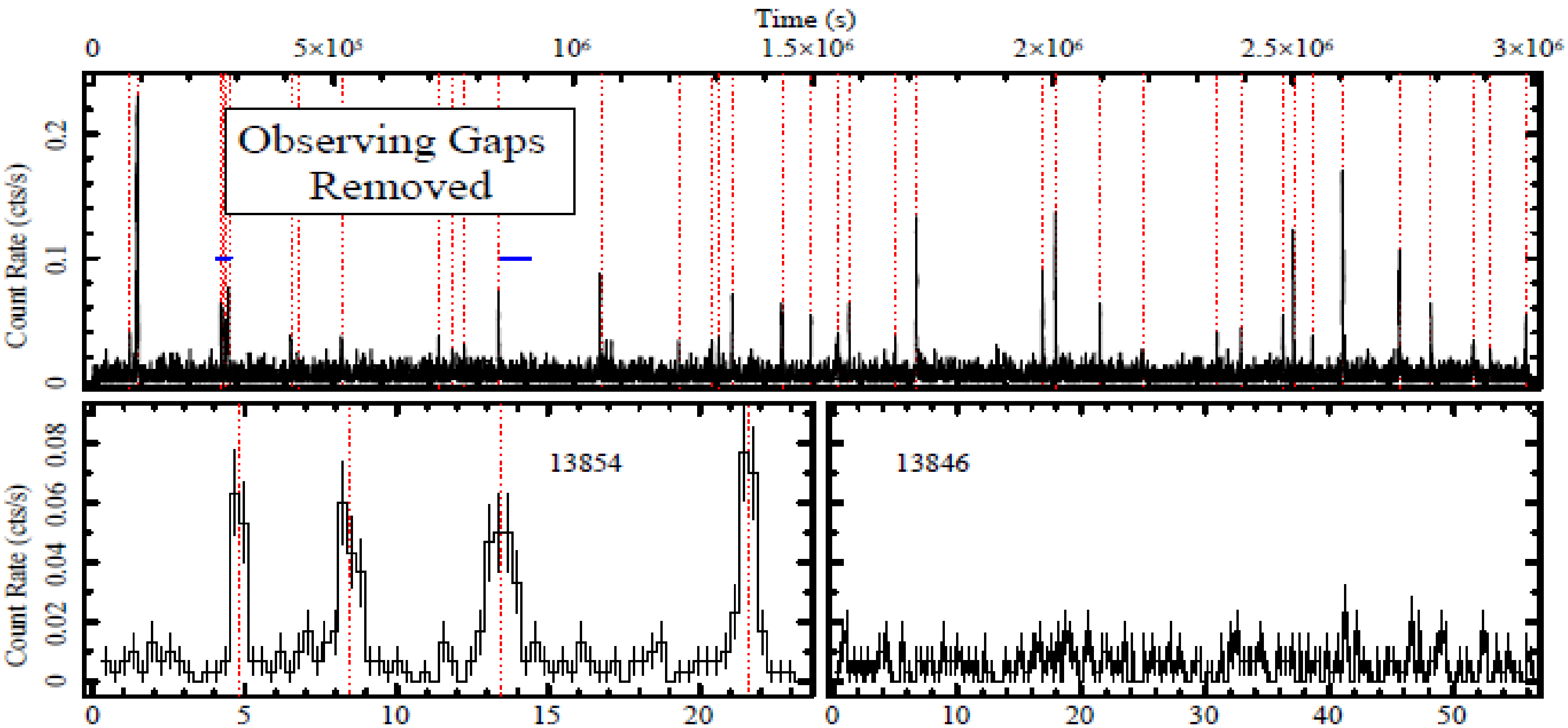


Flare emission originates from within <10mas form the position of SgrA*

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

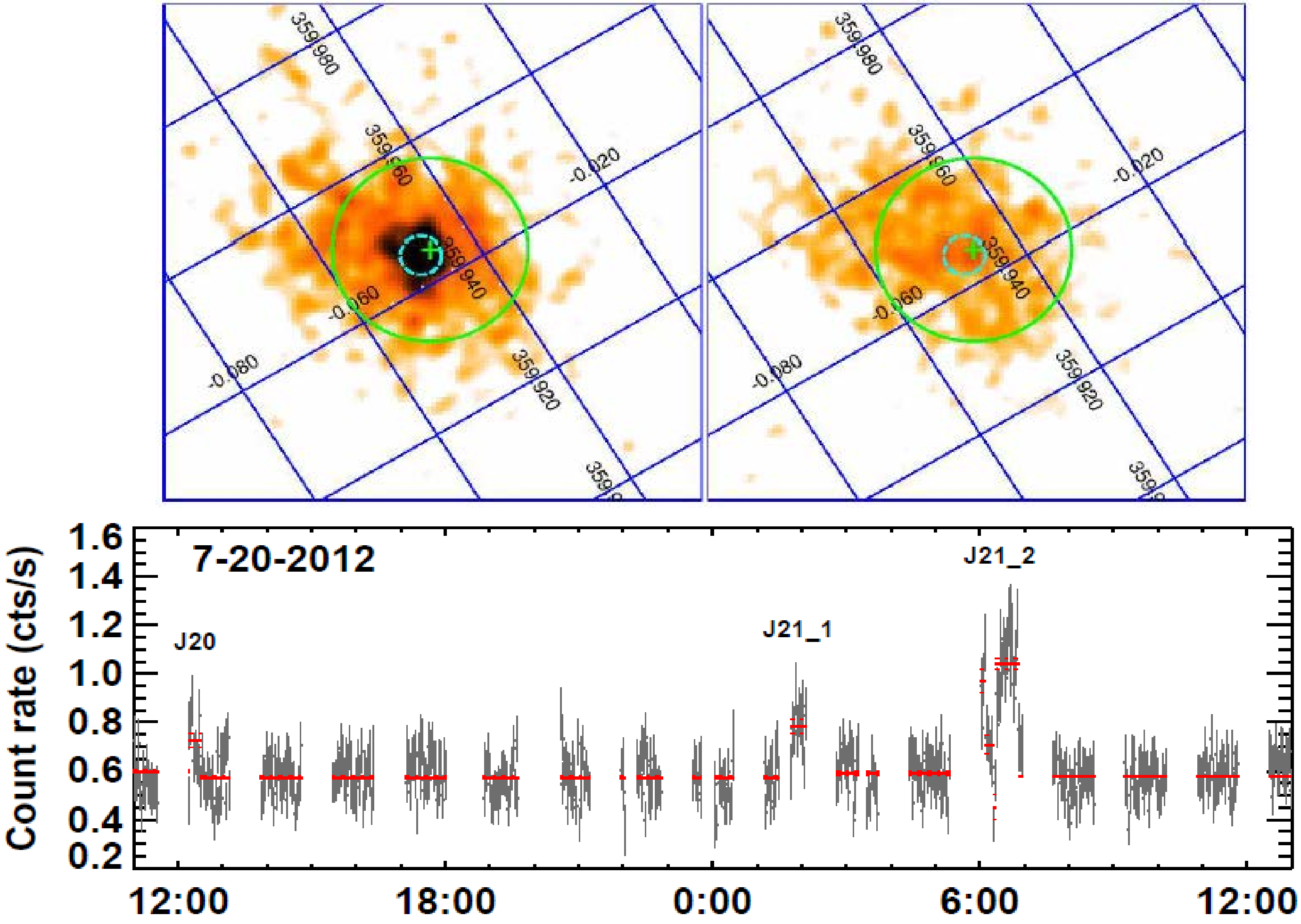
see also Yusef-Zadeh+ 2008, Marrone+ 2008, Porquet+203/08, Bower+ 2014

Chandra X-ray flare statistics in the 2-8 keV band



Neilsen, Novak et al. 2013: 39 detected flares in the 3Ms X-ray Visionary Project (XVP) observations. **Mean X-ray flare rate: ~1 per day; (NIR ~4/day);** mean X-ray flare luminosity 5x10^34 erg/s (10 times fainter than the brightest Chandra flare; Novak et al. 2012); up to Γ=2; dN/dL~L^(-1.9+-0.4)

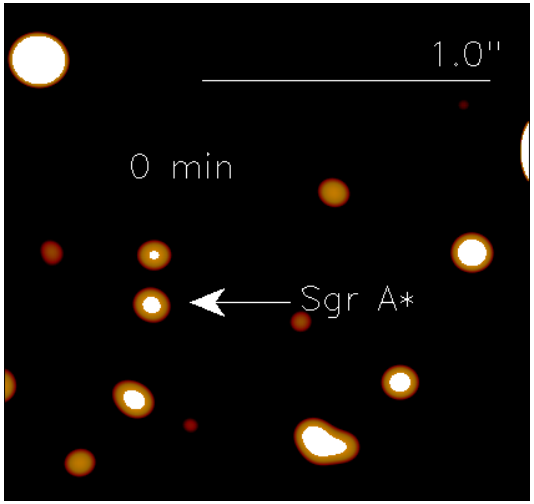
2012 NuSTAR flares in the 3-79 keV band



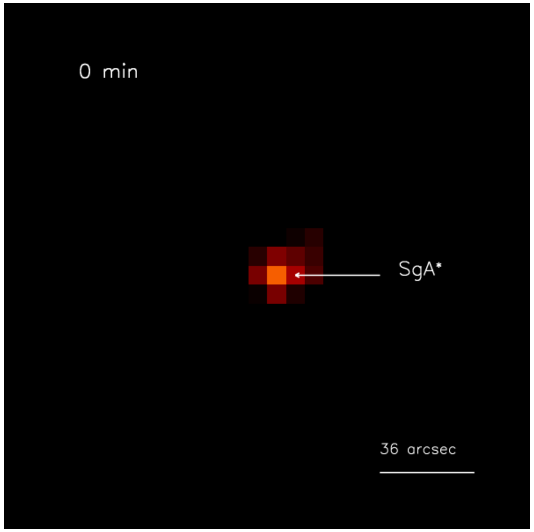
Barriere et al. 2014

NuSTAR‘s focal plane module A images (4.5‘x4.5‘) of the July 2012 flare J21_2 on and off the event including the light curve.

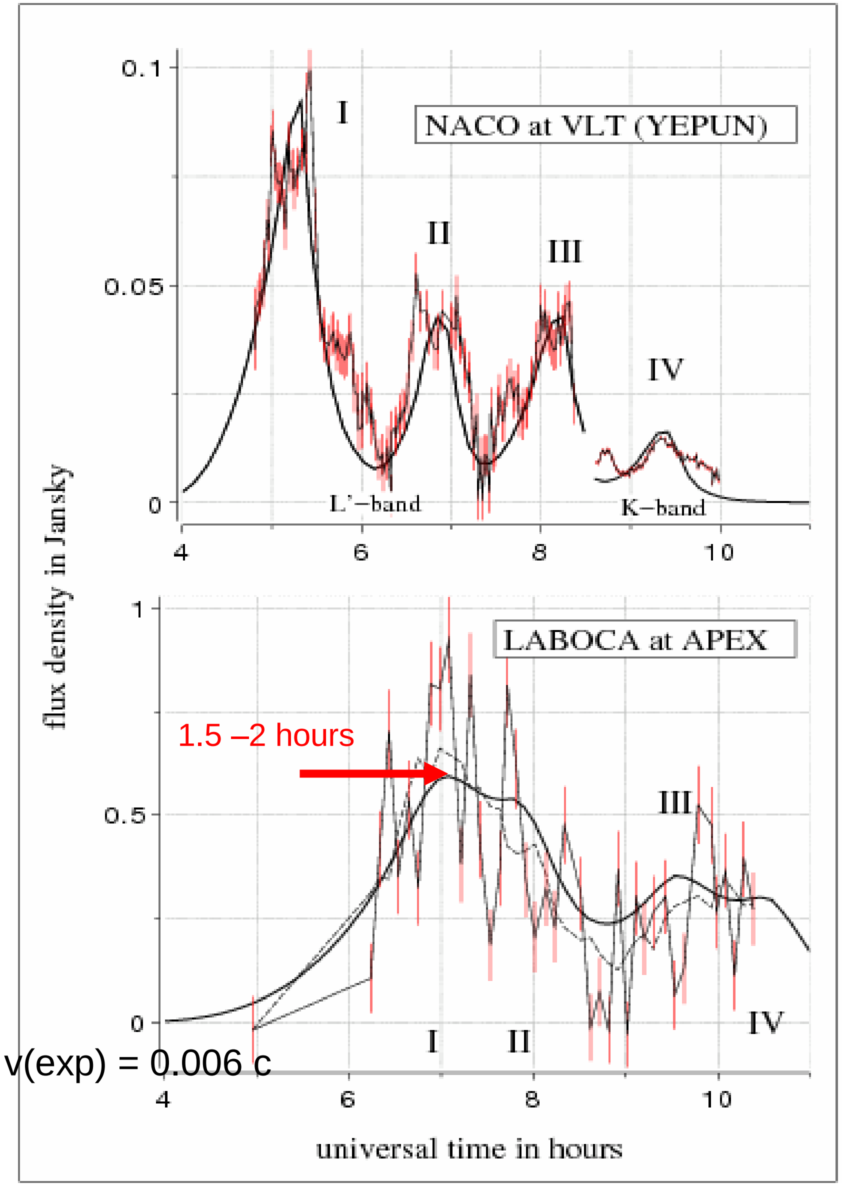
SgrA* on 3 June 2008:
VLT L-band and APEX
sub-mm measurements



VLT 3.8um L-band



APEX 1.3 mm



v(exp) = 0.006 c

Eckart et al. 2008; A&A 492, 337
Garcia-Marin et al.2009

Flare Emission from SgrA*

Recent work on SgrA* variability

Radio/sub-mm:

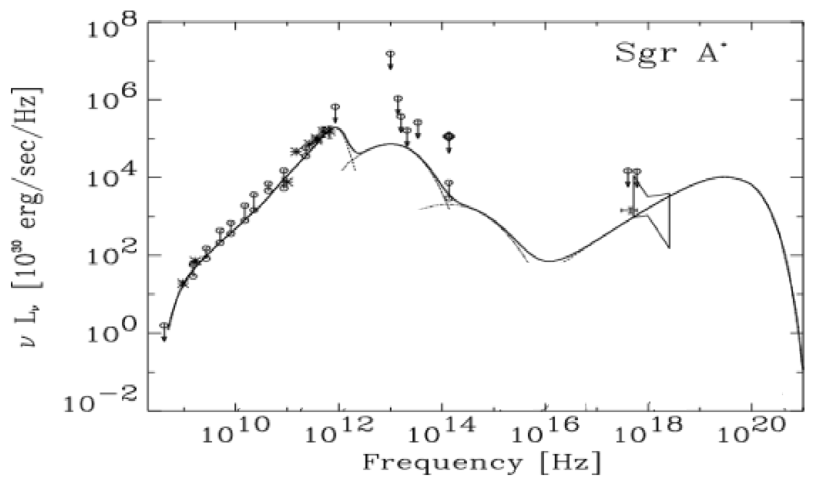
Mauerhan+2005, Marrone+2006/8, Yusef-Zadeh+2006/8, Doeleman+ 2009, 2012, and may others

X-ray:

Baganoff+2001/3, Porquet+2003/2008, Eckart+2006/8, Neilsen et al. 2013, and several others

NIR:

Genzel+2003, Ghez+2004, Eckart+2006/9, Hornstein+2007,Do+2009, and many others



Multi frequency observing programs:

Genzel, Ghez, Yusef-Zadeh, Eckart, Bower and many others

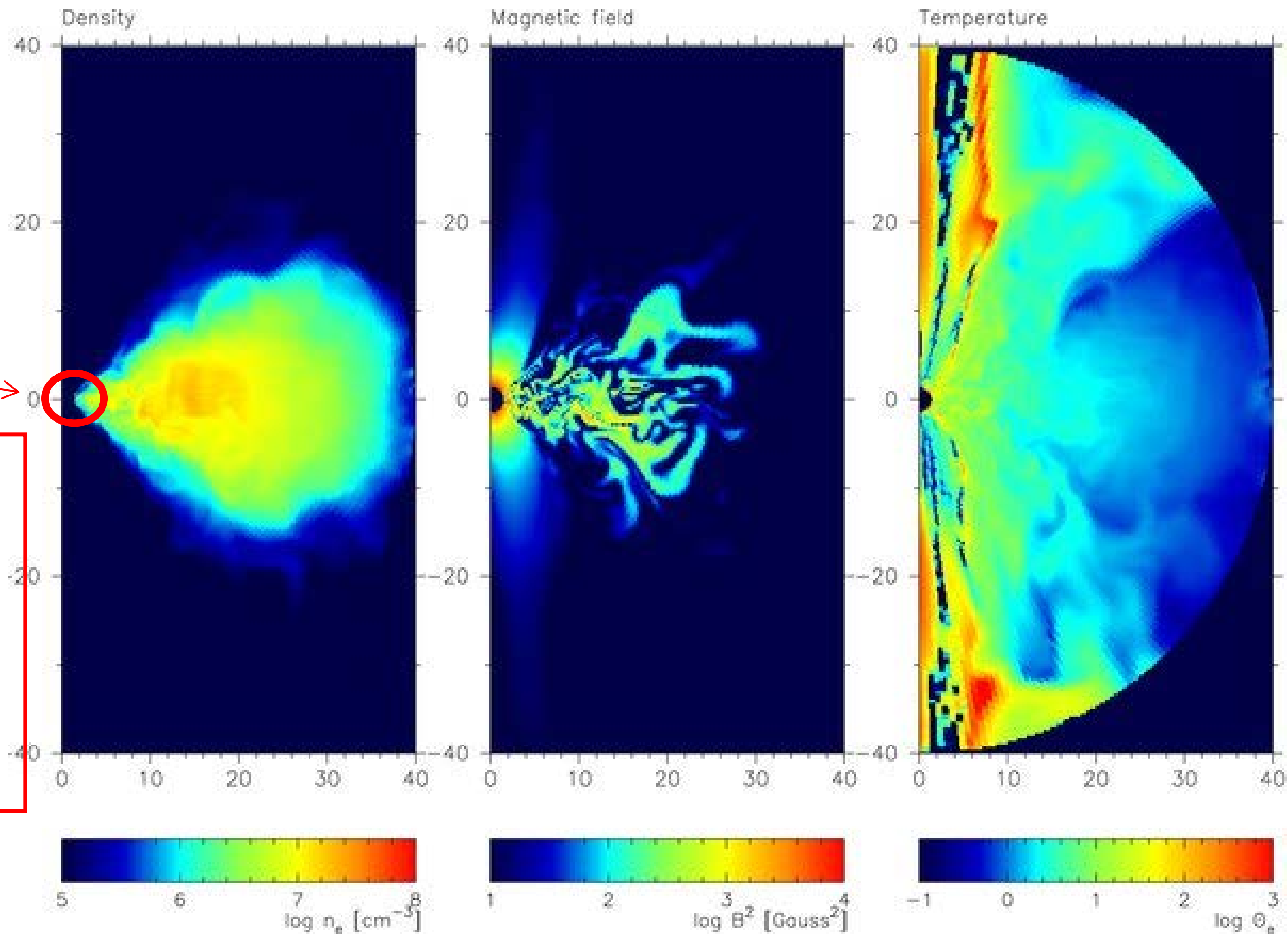
Questions:

- What are the radiation mechanisms
- (How) Are flux density variations at different wavelength connected to each other

Radiative Models of SGR A* from GRMHD Simulations

MOTION IN OR CLOSE TO THE MIDPLANE

relativistic effects may become observable here



Accretion of matter onto SgrA* results in a variable spectrum

Mościbrodzka+ 2010, 2009
Dexter+ 2010

Synchrotron Modeling

Rapid variability time scales (< 1hour) imply a non-thermal radiation mechanism:

$$S_{X,ssc} = d(\alpha)\ln(\frac{\nu_2}{\nu_m})\theta^{-2(2\alpha+3)}\nu_m^{-(3\alpha+5)}S_n^{2(\alpha+2)}E_X^{-\alpha}\delta^{-2(\alpha+2)},$$

$$B = 10^{-5}b(\alpha)\theta^4\nu_m^5 S_m^{-2}\delta,$$

$$N_0 = n(\alpha)D_{Gpc}^{-1}\theta^{-(4\alpha+7)}\nu_m^{-(4\alpha+5)}S_m^{2\alpha+3}\delta^{-2(\alpha+2)},$$

Marscher 1983, 2009

Visualization of possible flare scenarii

relativistic electron density

$$S_m = \kappa_1 \nu^{-\alpha}$$

$$\theta = \kappa_2 \nu_m^{\zeta_1}$$

$$B = \hat{\rho} \nu_m^{\zeta_2}$$

$$N_0 = \kappa_3 \nu_m^{\zeta_3}$$

$$\rho = mc^2 \int_{\gamma_1}^{\gamma_2} N(\gamma) d\gamma = N_0 \frac{(mc^2)^{-2\alpha}}{2\alpha} (\gamma_1^{-2\alpha} - \gamma_2^{-2\alpha})$$

$$N(\gamma) = N_0 E(\gamma)^{2\alpha+1}$$

All important quantities can be written as powers of the turnover frequency.

All constants are functions of observables (spectral index and fluxes) or parameters

Eckart et al. 2012

Visualization of possible flare scenarii

Possible flare models

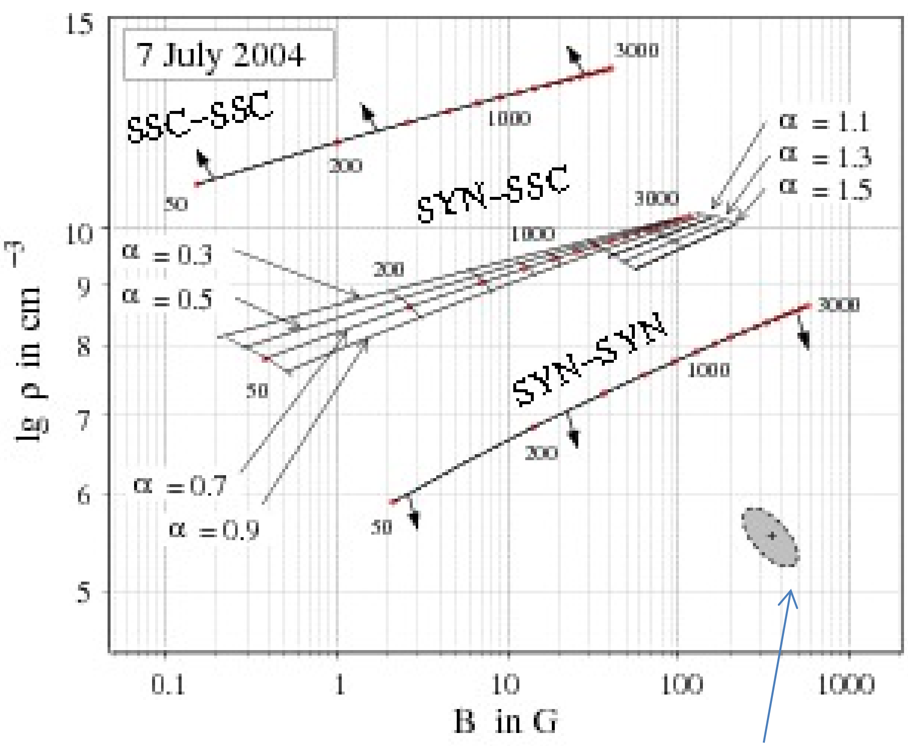
NIR X-ray

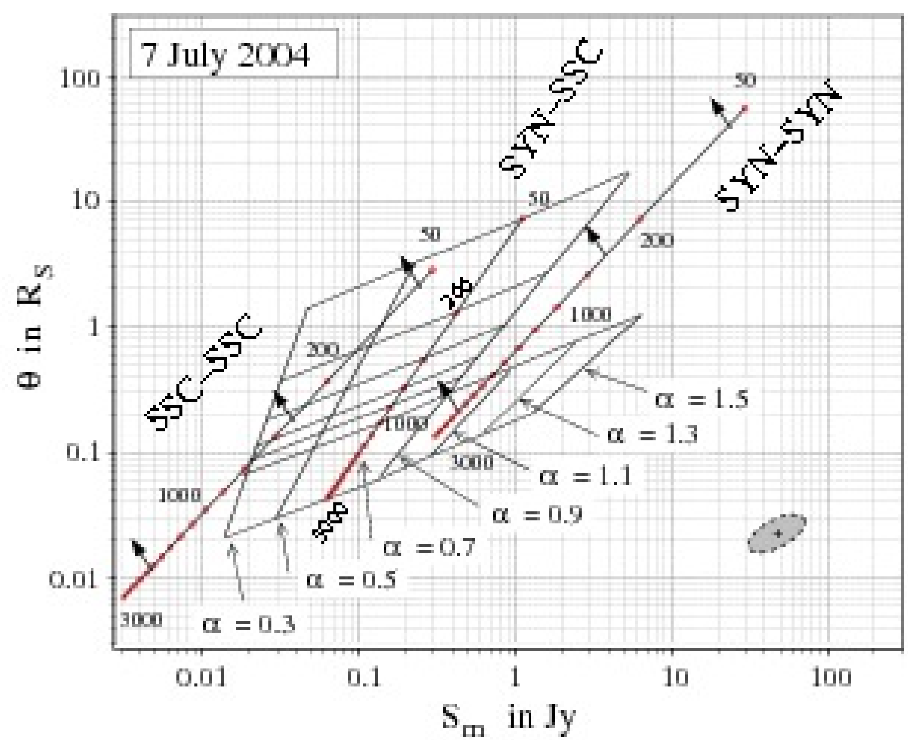
SYN-SYN: Synchrotron-synchrotron

SYN-SSC: Synchrotron-Self-Compton

SSC-SSC: Self-Compton-self-Compton

Visualization of possible flare scenarii





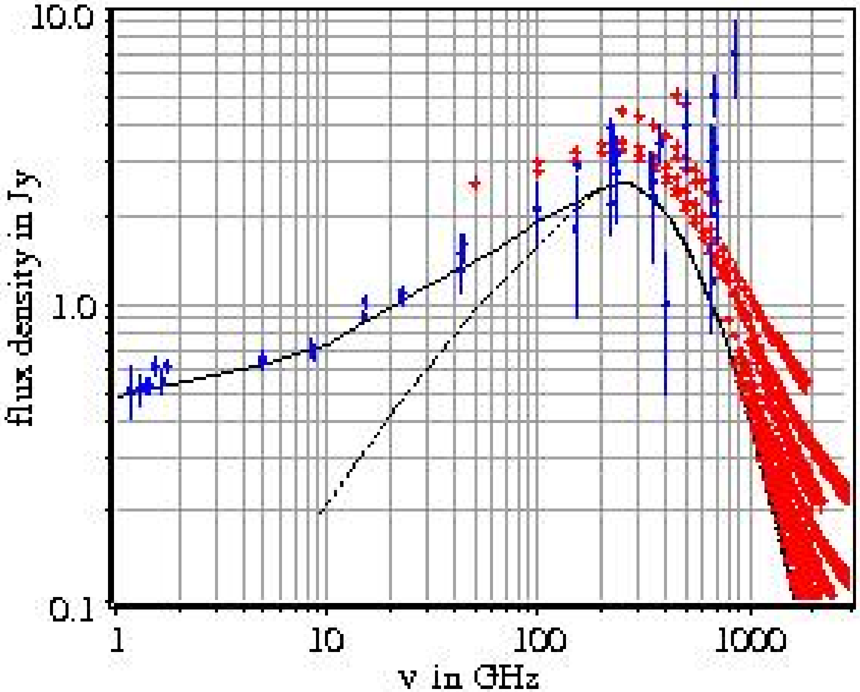
parameterized by case spectral index and turnover frequency νm.

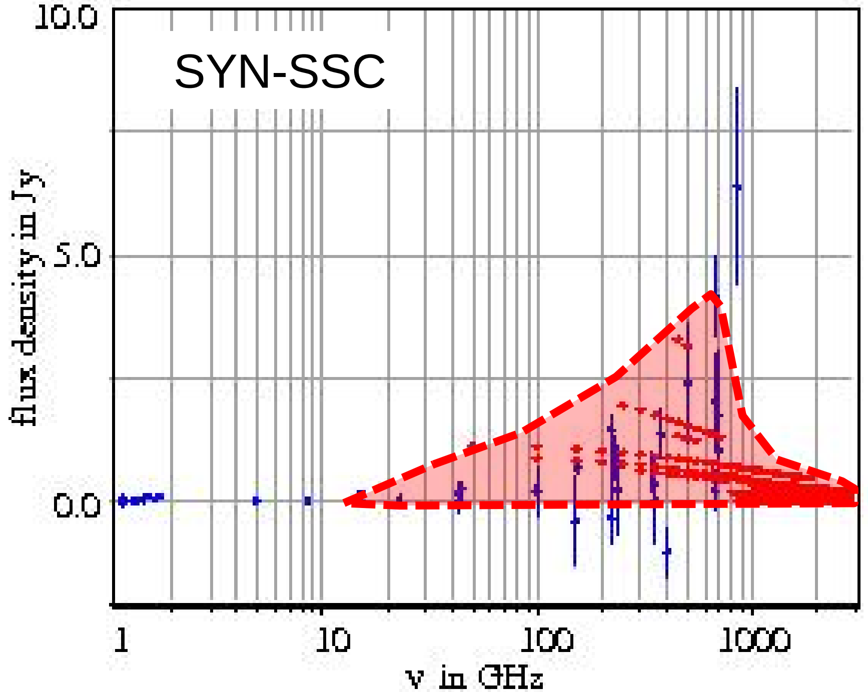
Uncertainties due to measurement uncertaintuies

Solutions obey MIR flux limits (Schödel+ 2010,11) and: If SYN dominates - then less than 10% of the radiation should be due to SSC and vice versa.
Arrows point into directions of even more stringent constrains.

Eckart et al. 2012

Variability in the SYN-SSC case



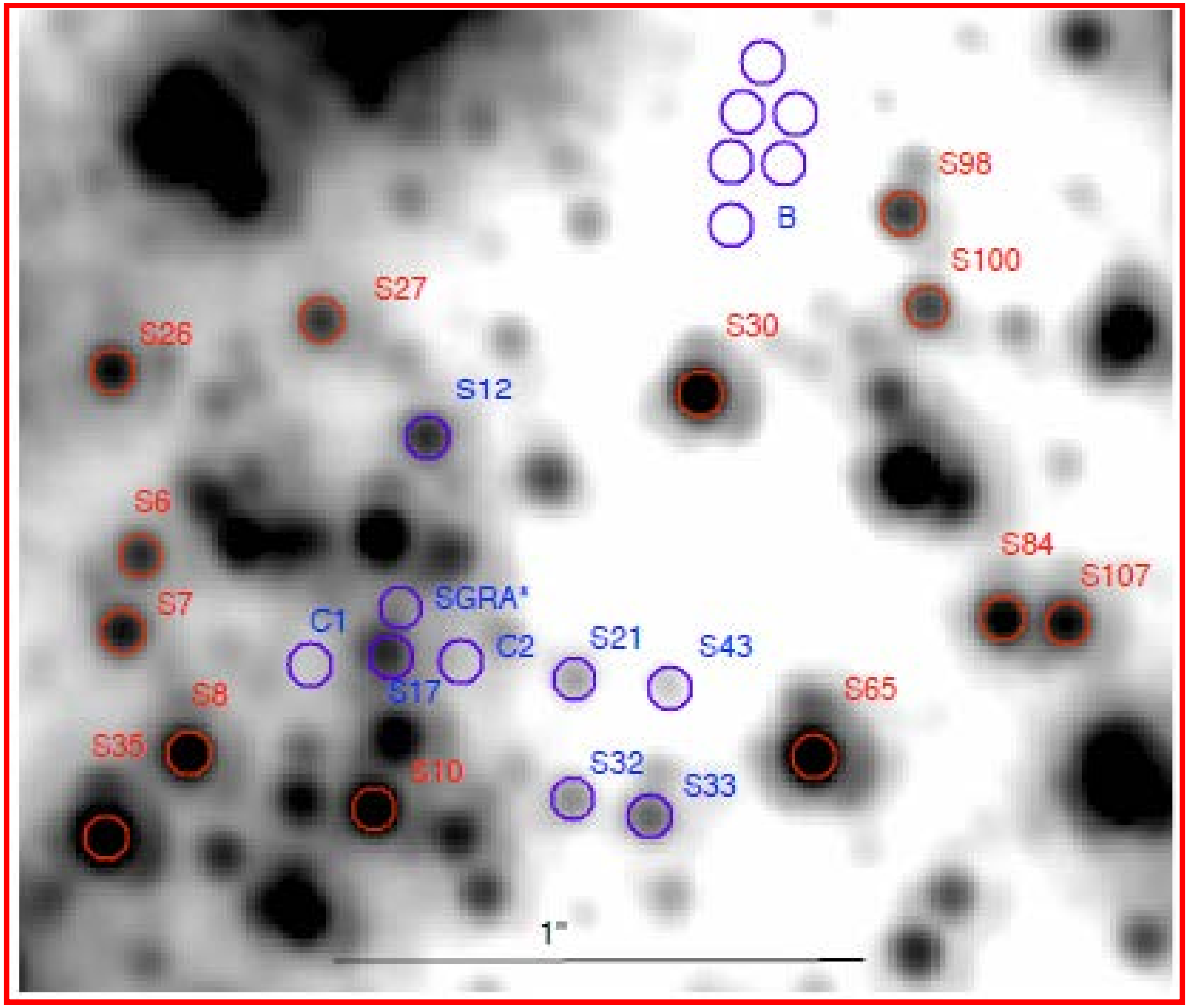


SYN-SSC: Density moderate;
consistent with MHD model of mid-plane;
Moderate demand on electron acceleration.

Eckart et al. 2012

Statistics of NIR light curves of SgrA*

Synchrotron radiation is responsible for flux density variations in the NIR – which can be studied there best – without confusion due to fluxes from the larger scale accretion stream.



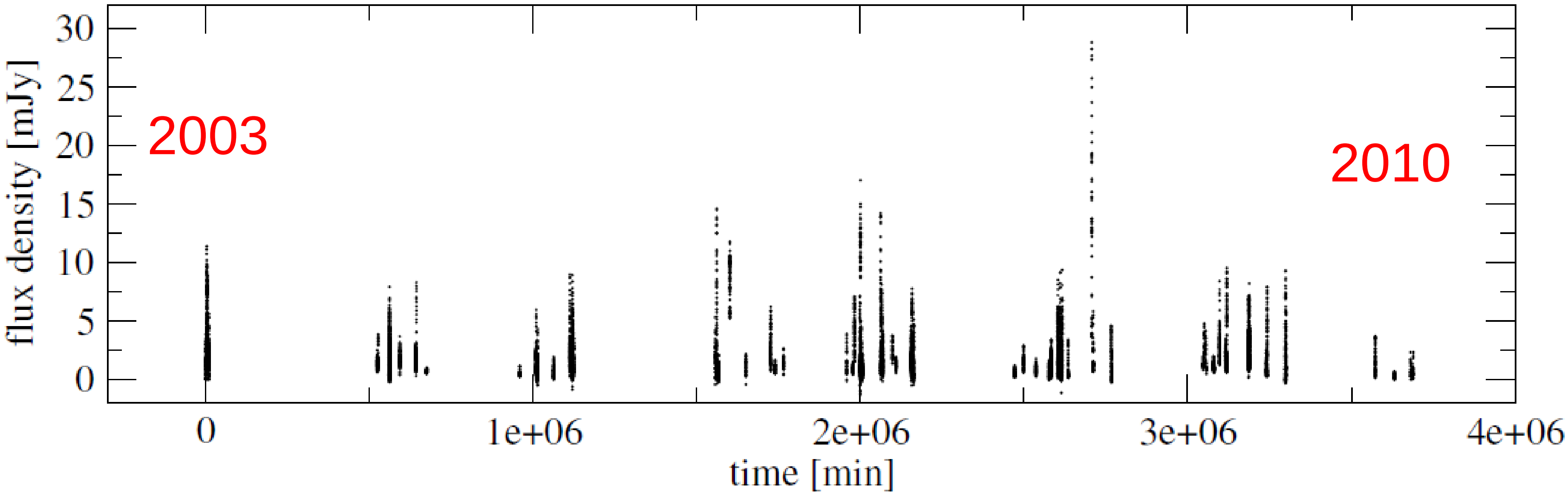
Measurements at 2 μm

Apertures on
(1) SgrA*.
(2) reference stars,
(3) and off-positions

Ks-band mosaic from 2004 September 30. The red circles mark the constant stars (Rafelski et al. 2007) which have been used as calibrators, blue the position of photometric measurements of Sgr A*, comparison stars and comparison apertures for background estimation (Witzel et al. 2012).

Witzel et al. 2012

NIR light curve of SgrA* over 7 years



Light curve of Sgr A*. Here no time gaps have been removed, the data is shown in its true time coverage. A comparison of both plots shows: only about 0.4% of the 7 years have been covered by observations.

Witzel et al. 2012

Flux density histogram for SgrA*

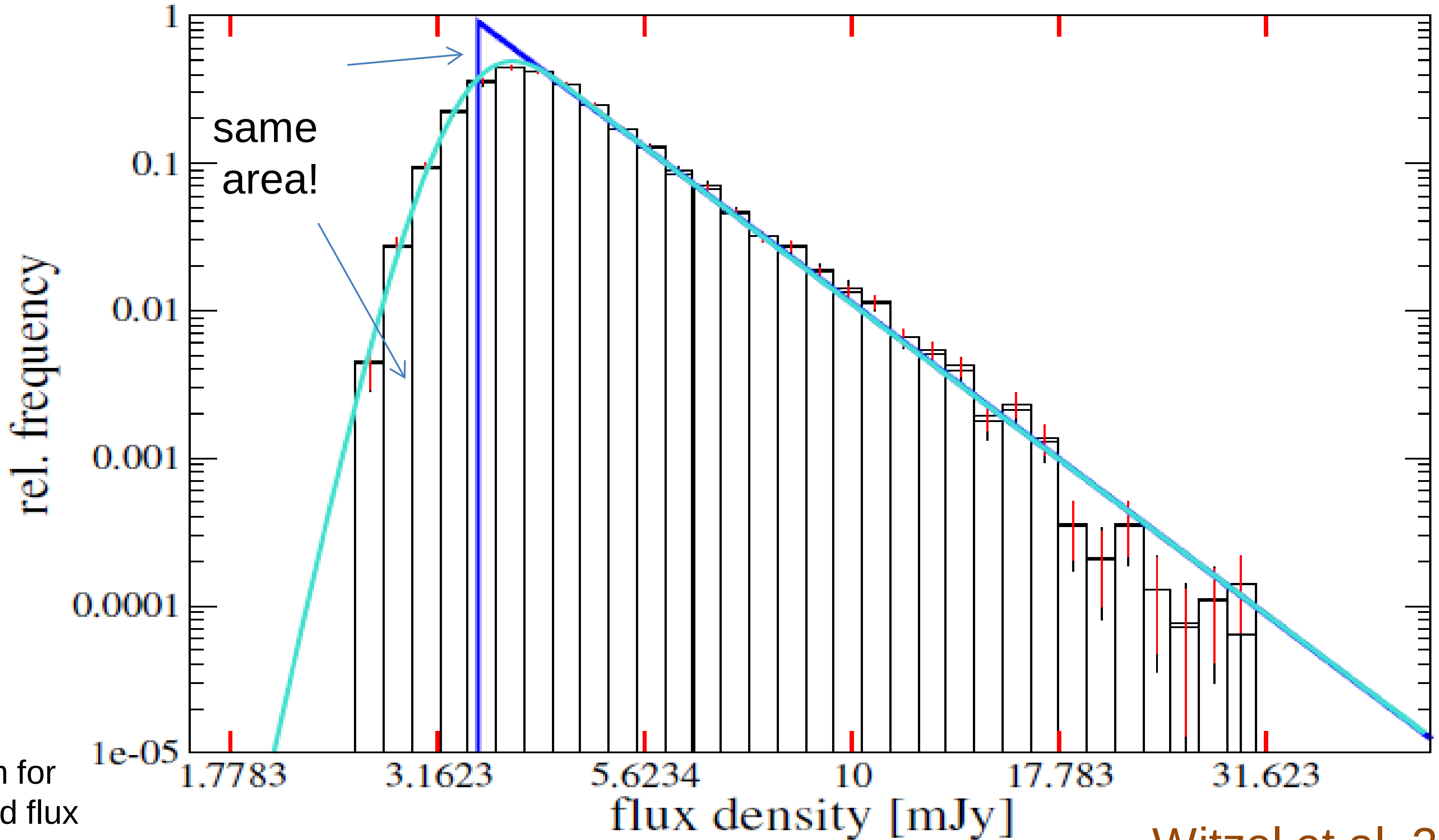
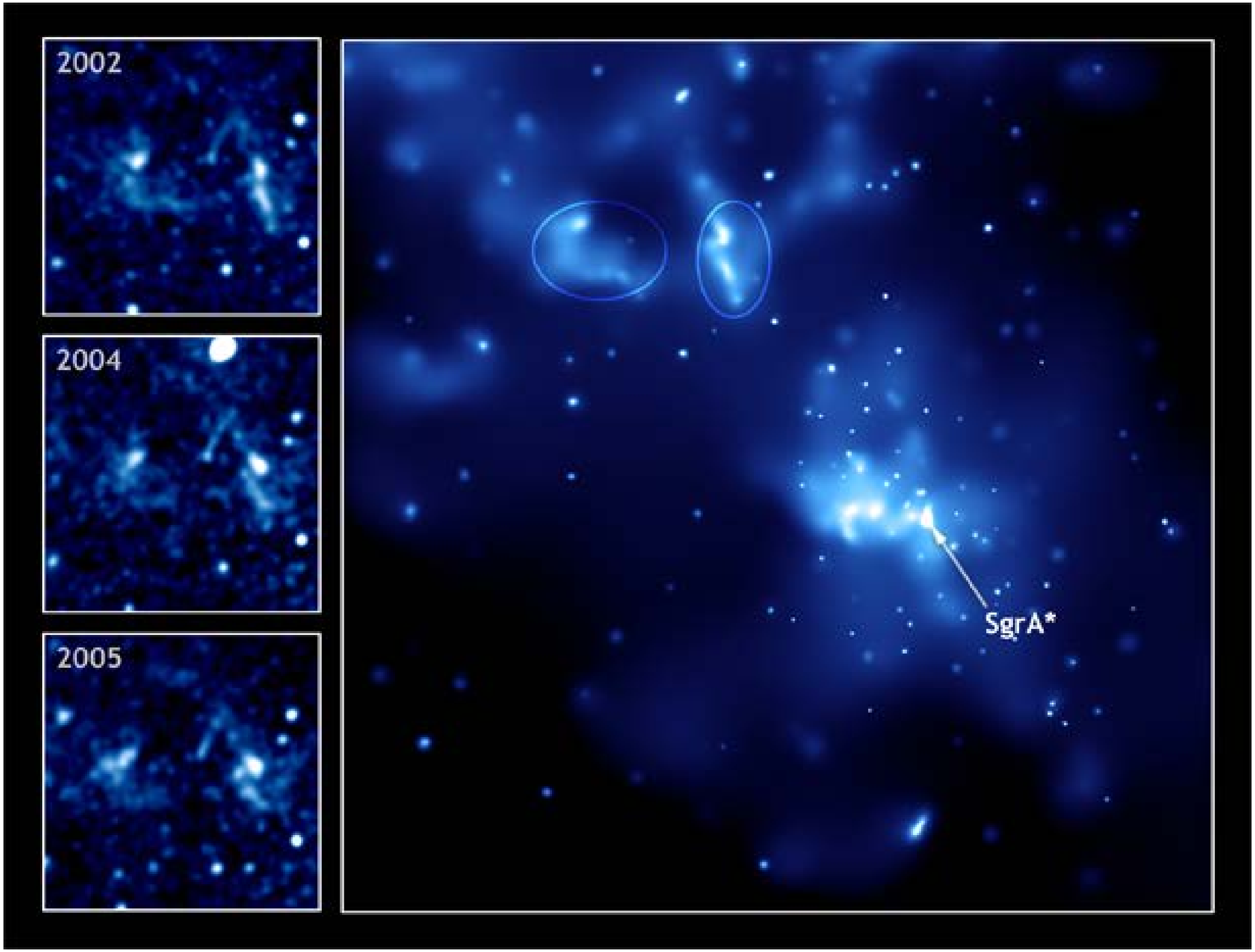


Diagram for polarized flux in work

Witzel et al. 2012

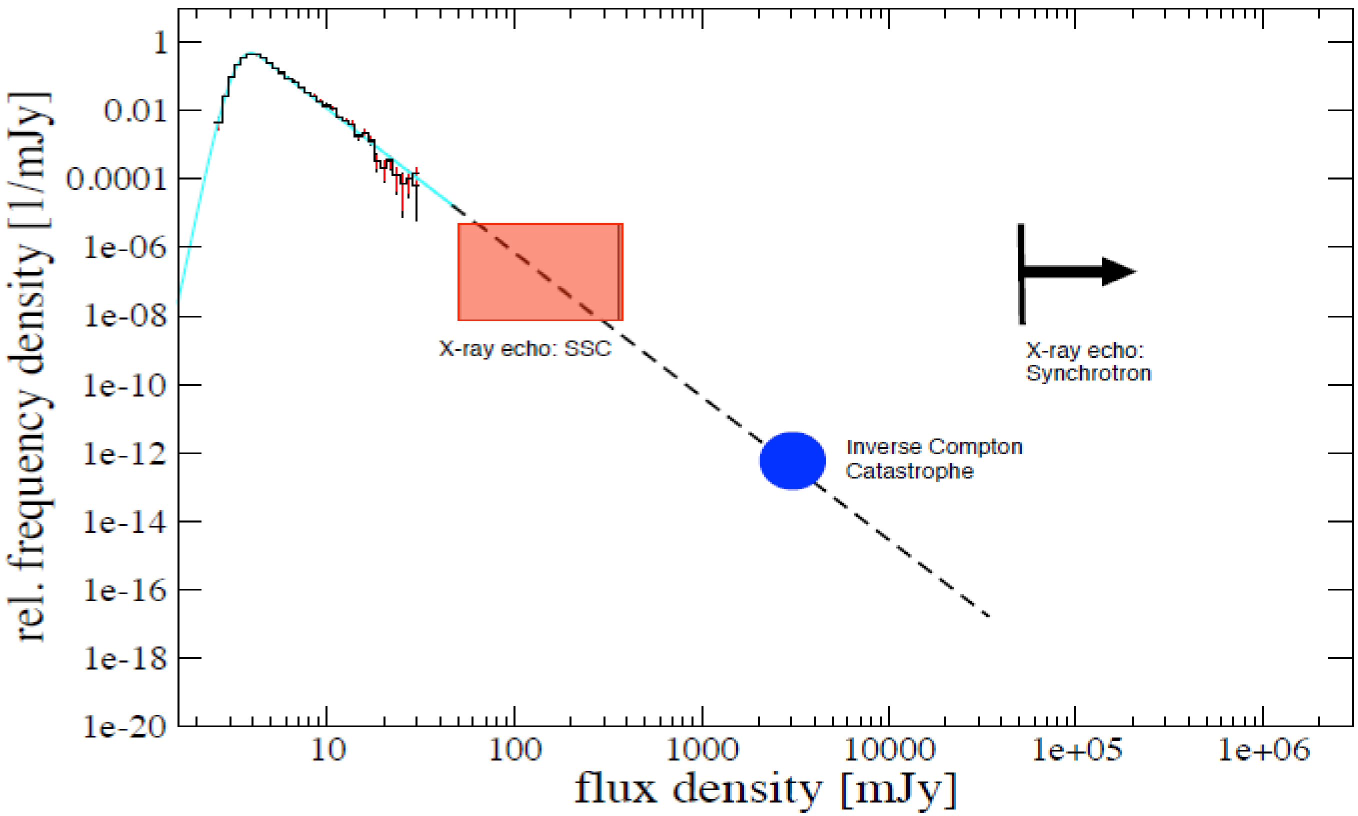
The brown line shows the extrapolation of the best power-law fit, the cyan line the power-law convolved with a Gaussian distribution with 0.32 mJy width.

X-ray light echo : variability of SgrA*



Chandra/ NASA

The statistics allows to explain the event 400 years ago that results in the observed X-ray light echo



Fluorescent back-scatter from molecular clouds surrounding the GC:

Revnivtsev et al. 2004, Sunyaev & Churazov 1998, Terrier et al. 2010

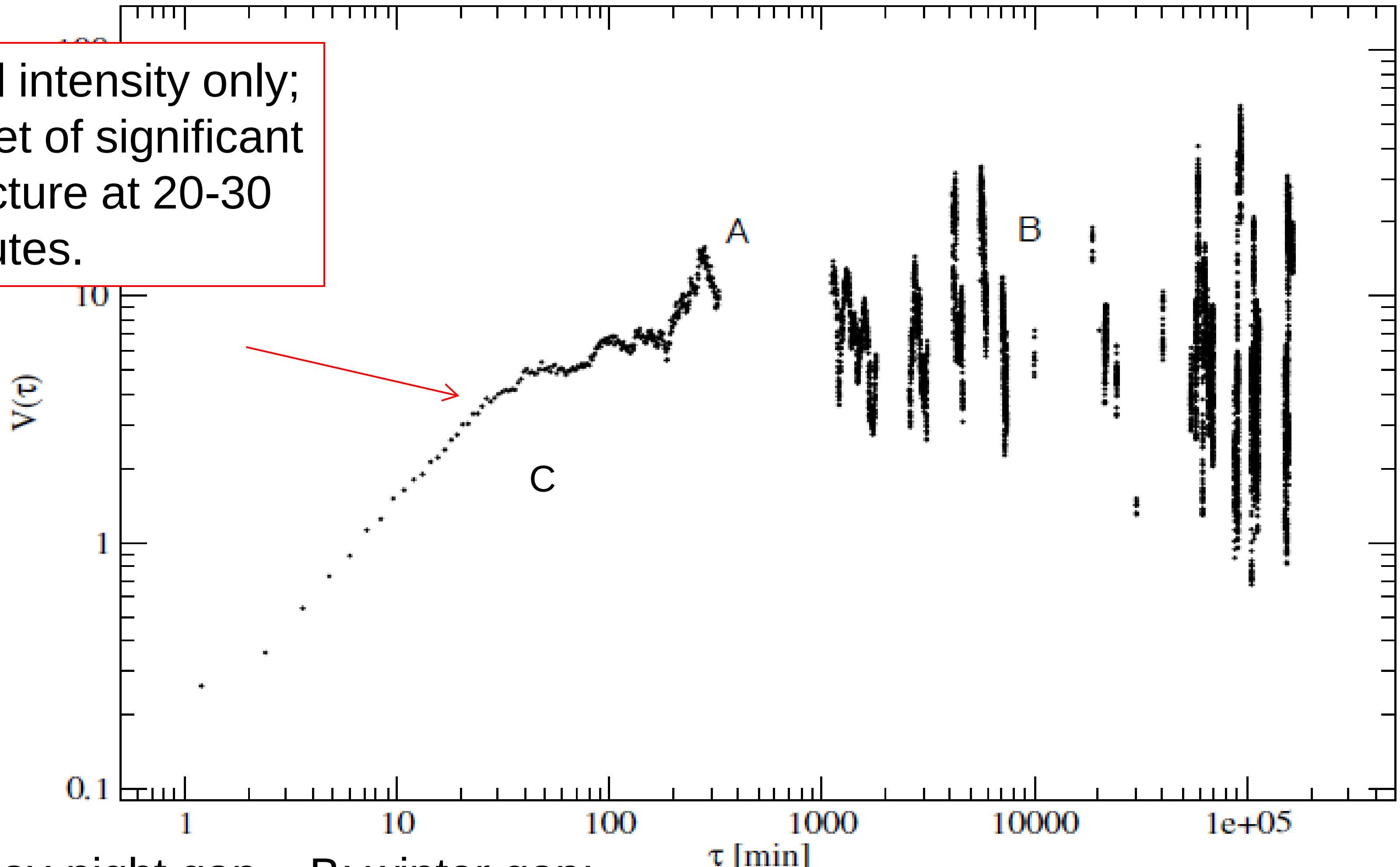
and

Witzel et al. 2012

Illustration of a flux density histogram extrapolated from the statistics of the observed variability. The expected maximum flux density given by the inverse Compton catastrophe and a estimation of its uncertainty is shown as the magenta circle, the SSC infrared flux density for a bright X-ray outburst as expected from the observed X-ray echo is depicted as the red rectangular.

Structure function of the SgrA*

Total intensity only; Onset of significant structure at 20-30 minutes.



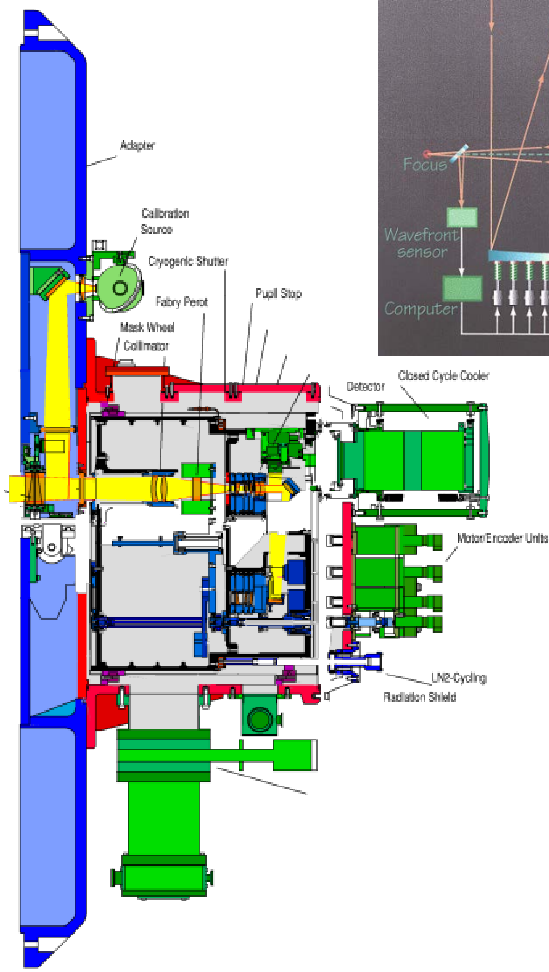
A: day-night gap, B: winter gap;
C: still influenced by window function;
time binning 1.2 min.

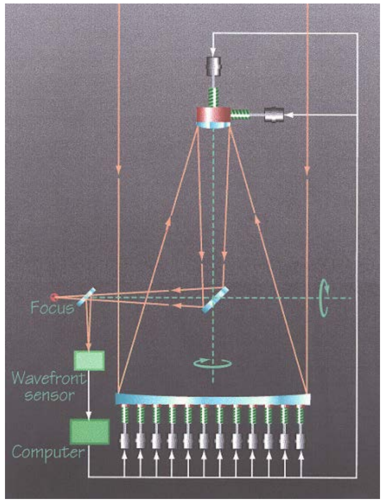
Witzel et al. 2012

NIR Polarization Signatures

Modeling of individual events
Relativistic Disk calculations

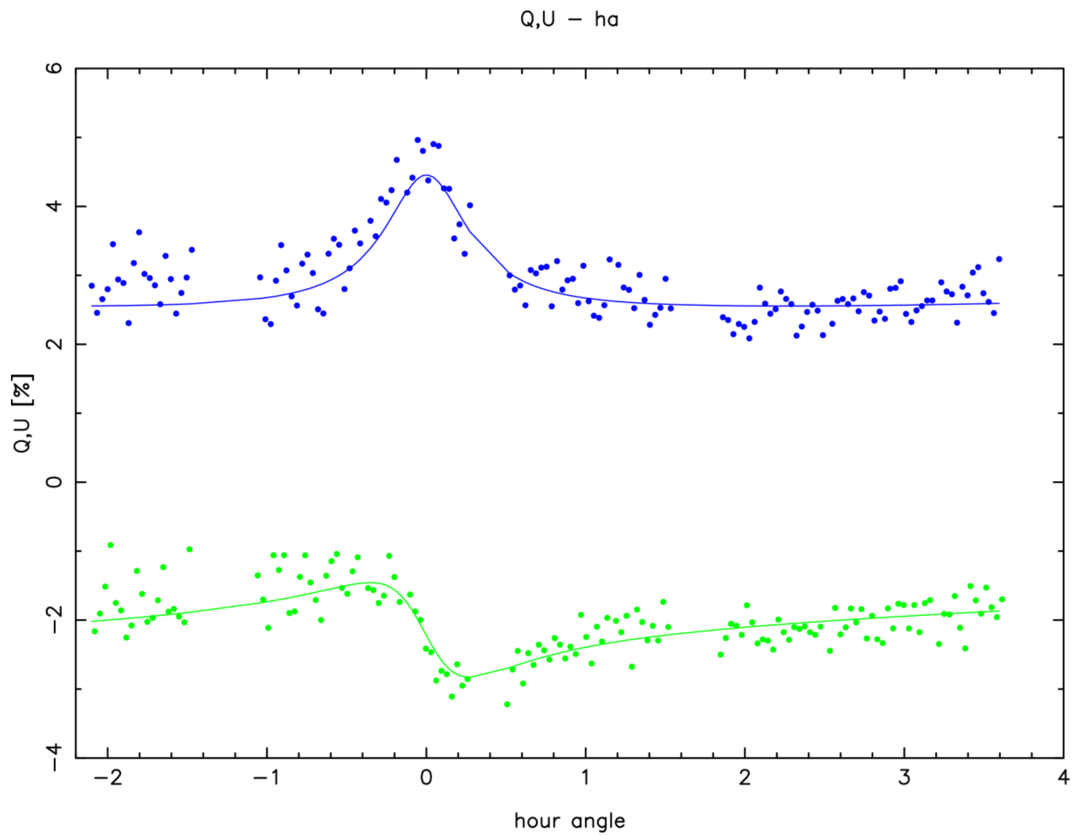
Precision of NIR Polarization measurements





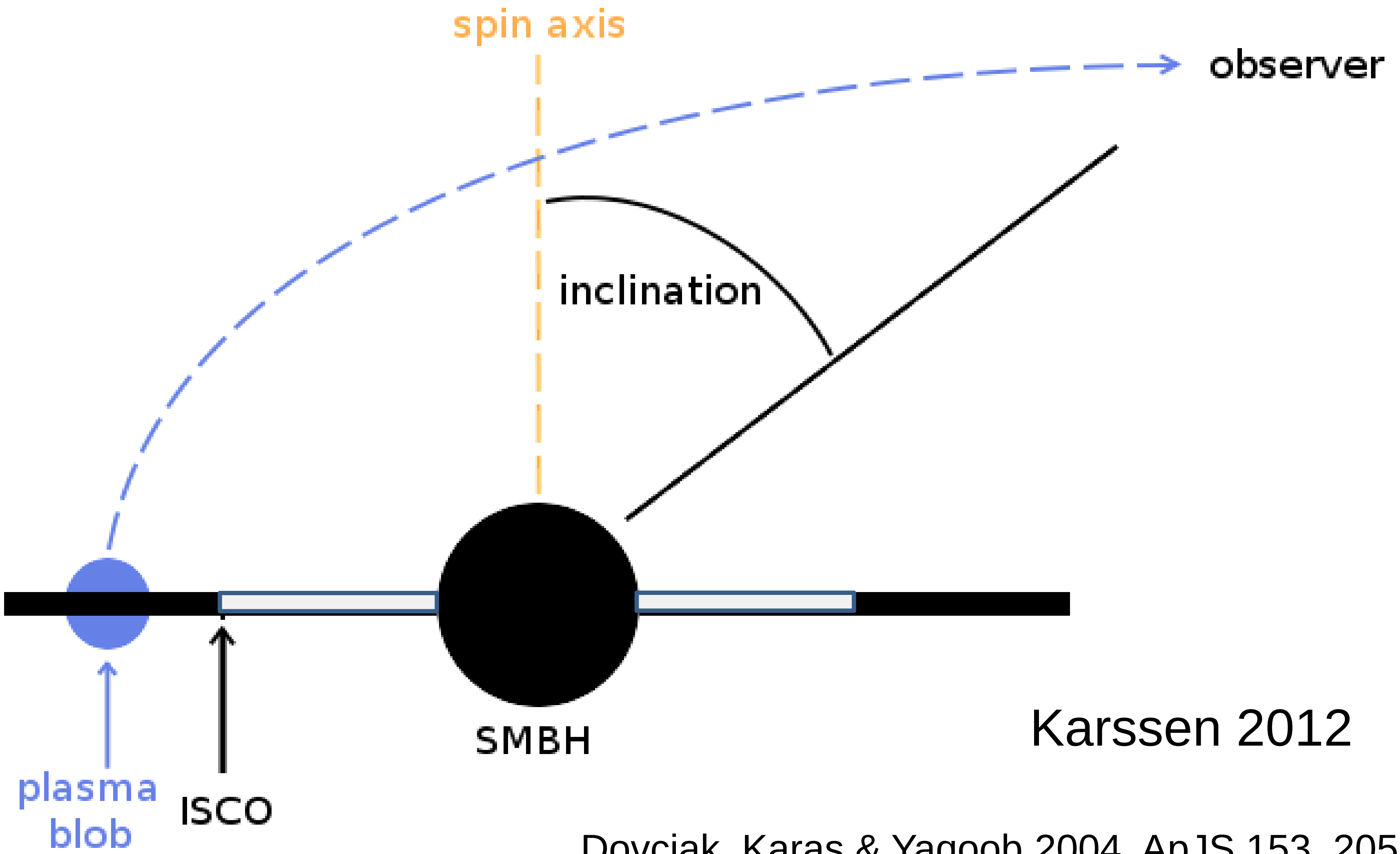
Instrument calibrated to ~1%

Current limit due to systematics ~3-4%



Witzel, G., et al. 2010

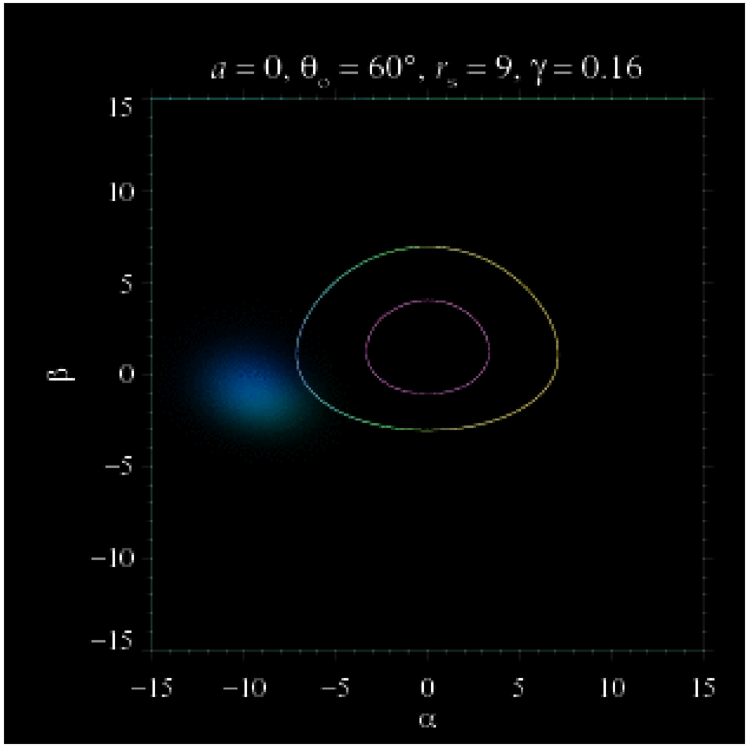
Geometry of Model

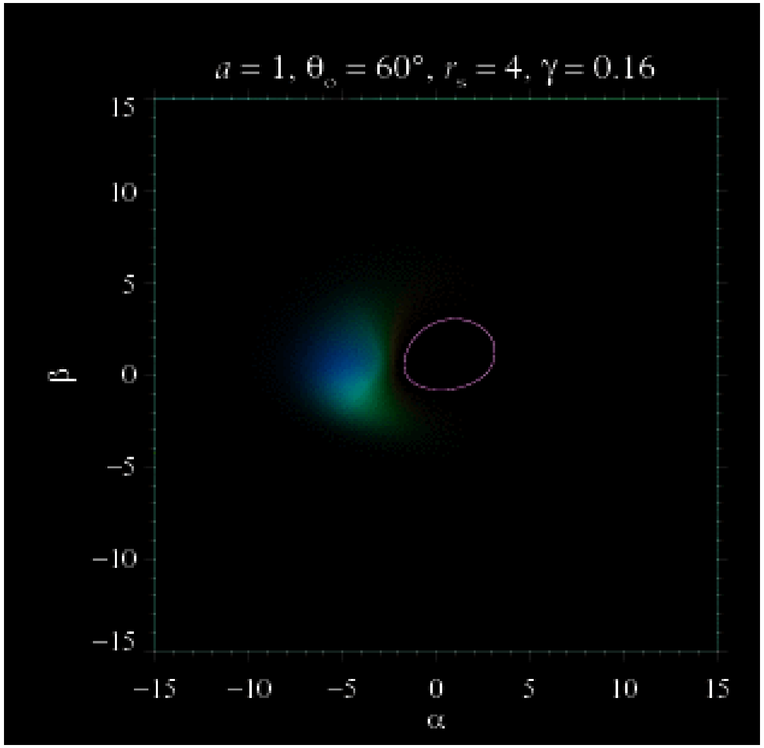


Karssen 2012

Dovciak, Karas & Yaqoob 2004, ApJS 153, 205
Dovciak et al. 2006

NIR Polarized Flux Density from SgrA*

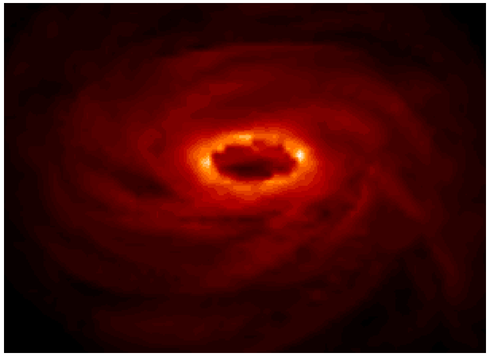




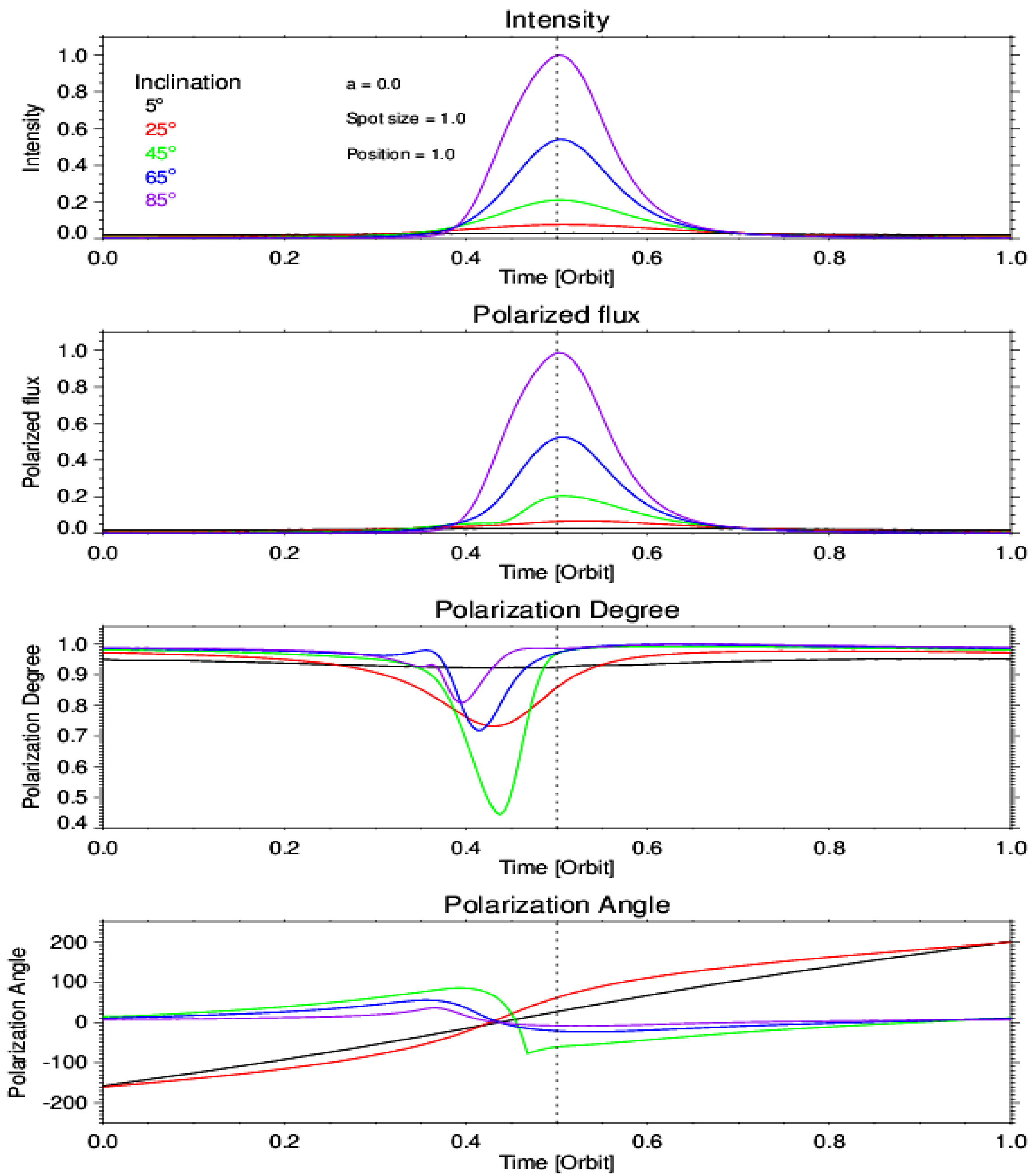
Dovciak, Karas & Yaqoob 2004, ApJS 153, 205
Dovciak et al. 2006

Goldston, Quataert & Igumenshchev 2005, ApJ 621, 785

see also Broderick & Loeb 2005 astro-ph/0509237
Broderick & Loeb 2005 astro-ph/0506433



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



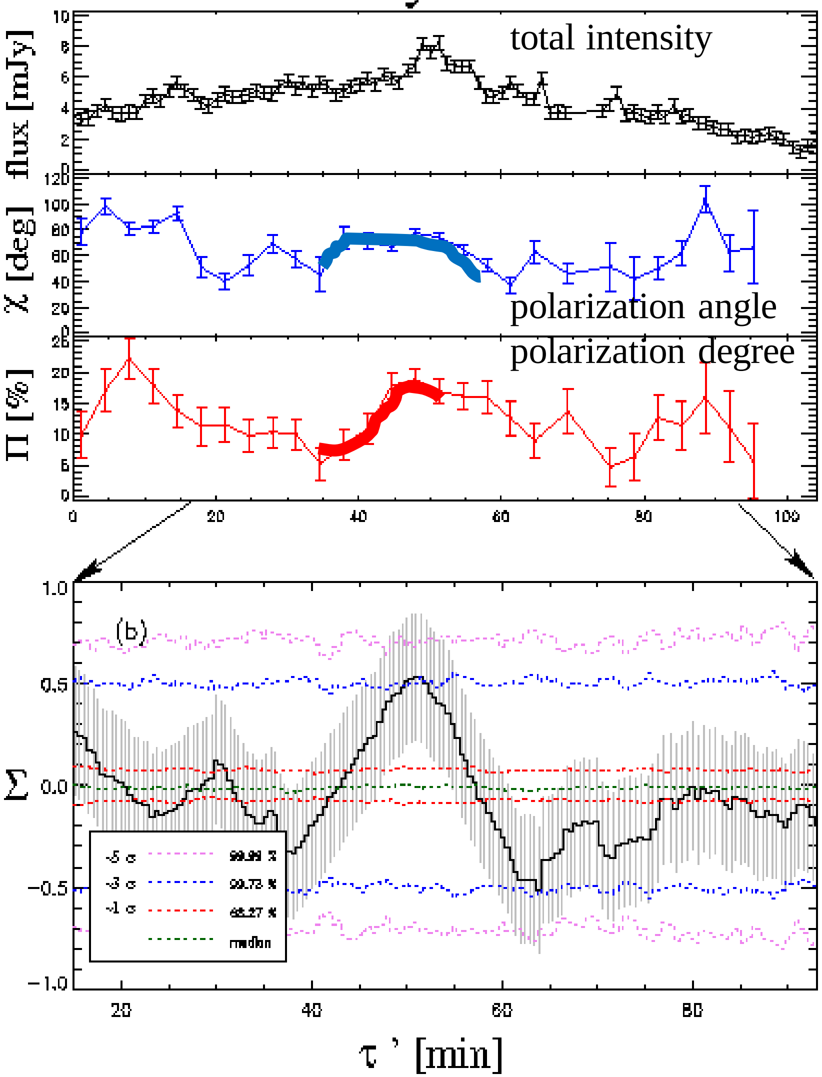
Vertical field case

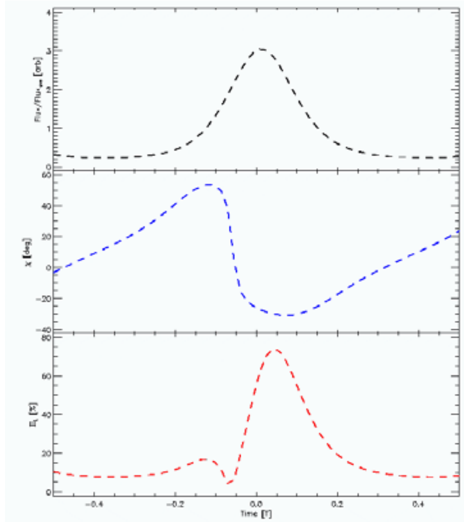
Karssen 2012

S. Karssen
M. Valencia-S.
M. Bursa,
M. Dovciak,
V. Karas
A. Eckart

Pattern recognition against polarized red noise

30 July 2005





Indication of relativistically orbiting matter!

5σ

3σ

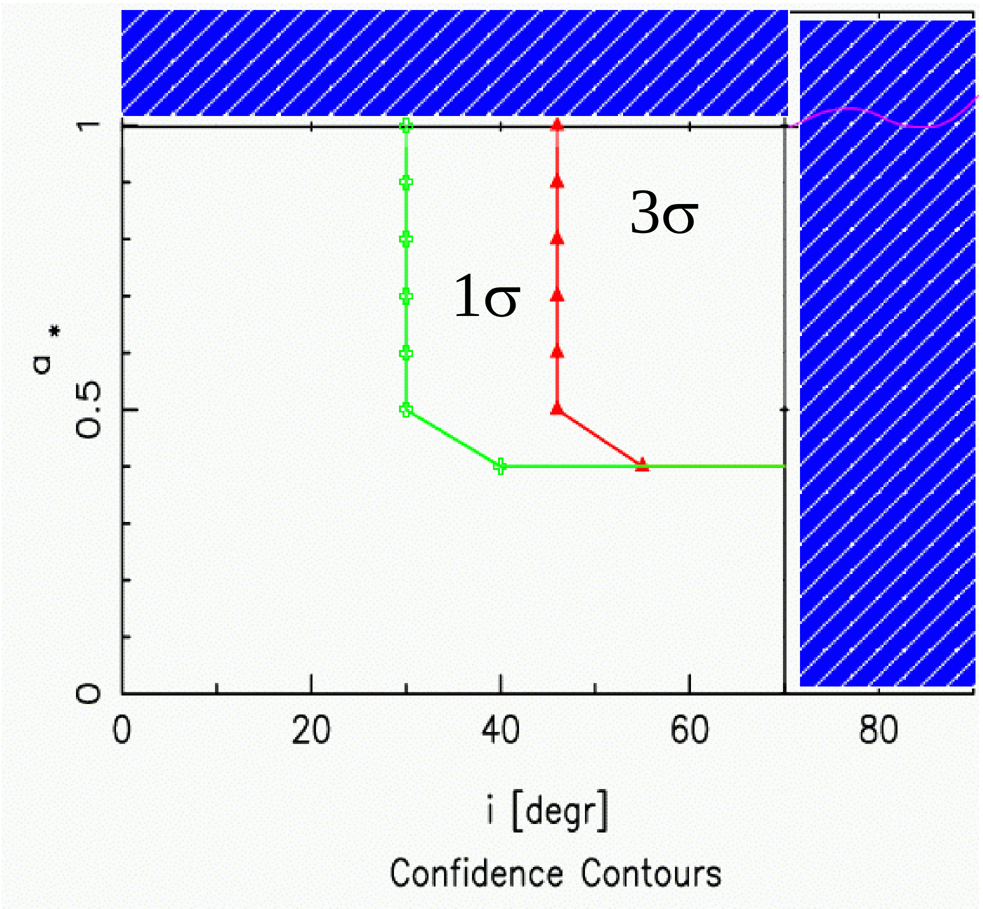
1σ

mean

randomly polarized red noise

Zamaninasab et al. 2009

NIR Polarized Flux Density from SgrA*

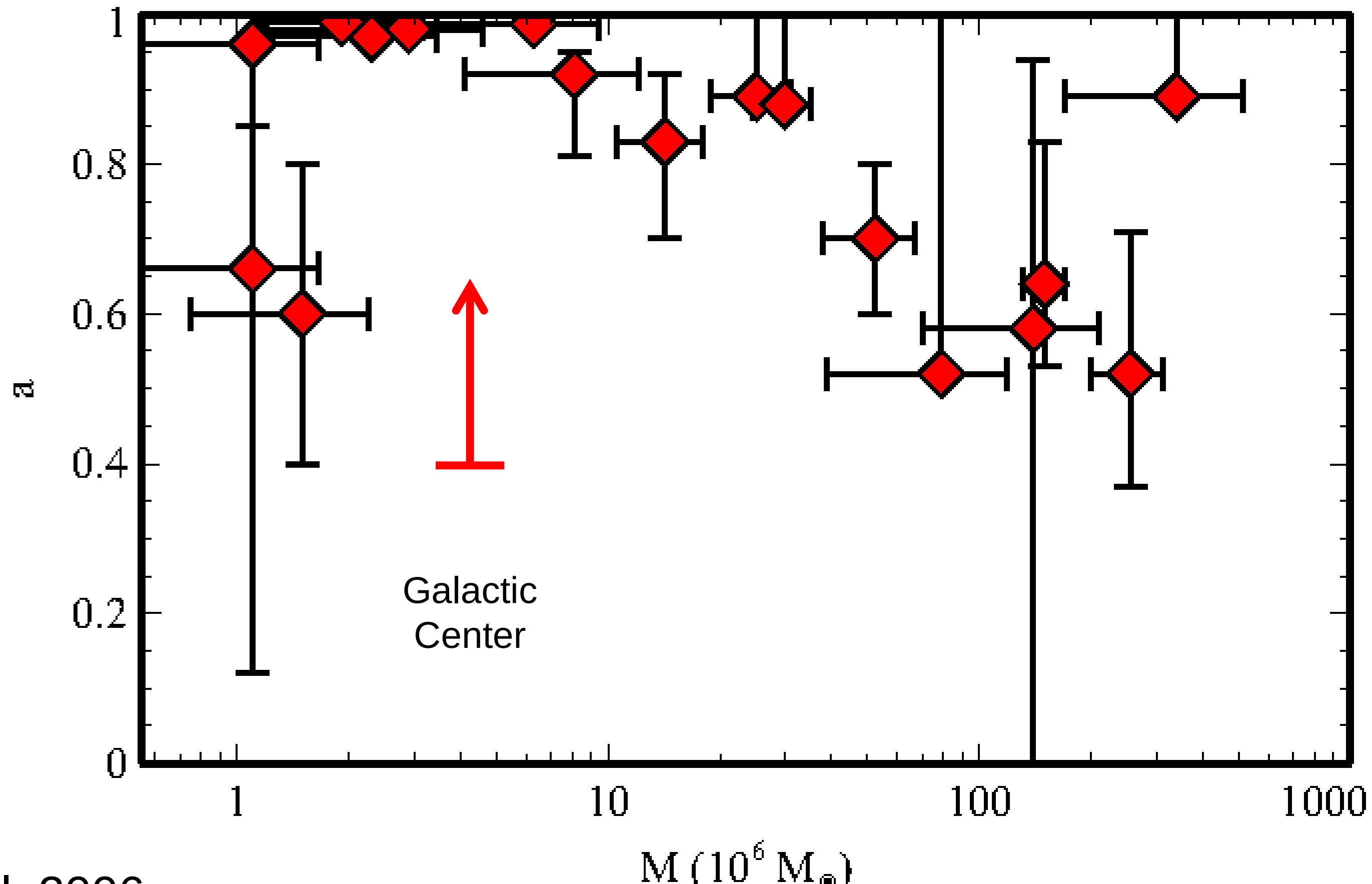


χ^2 analysis indicates
a= 0.4-1
$i=50^o$-70^o

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

Spin determination for SgrA*

accretion dominated spin? - versus - merger dominated spin?

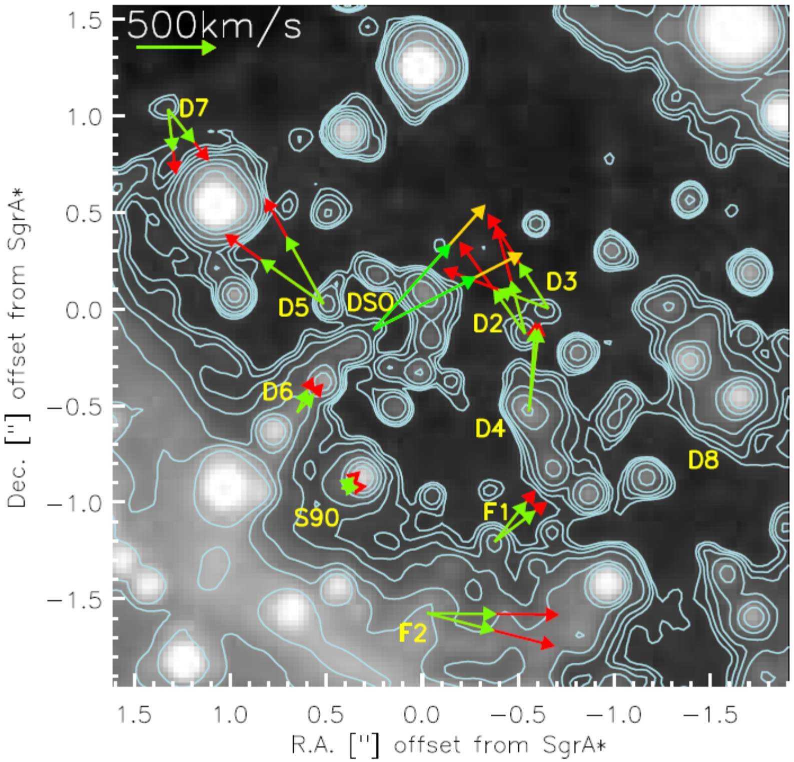


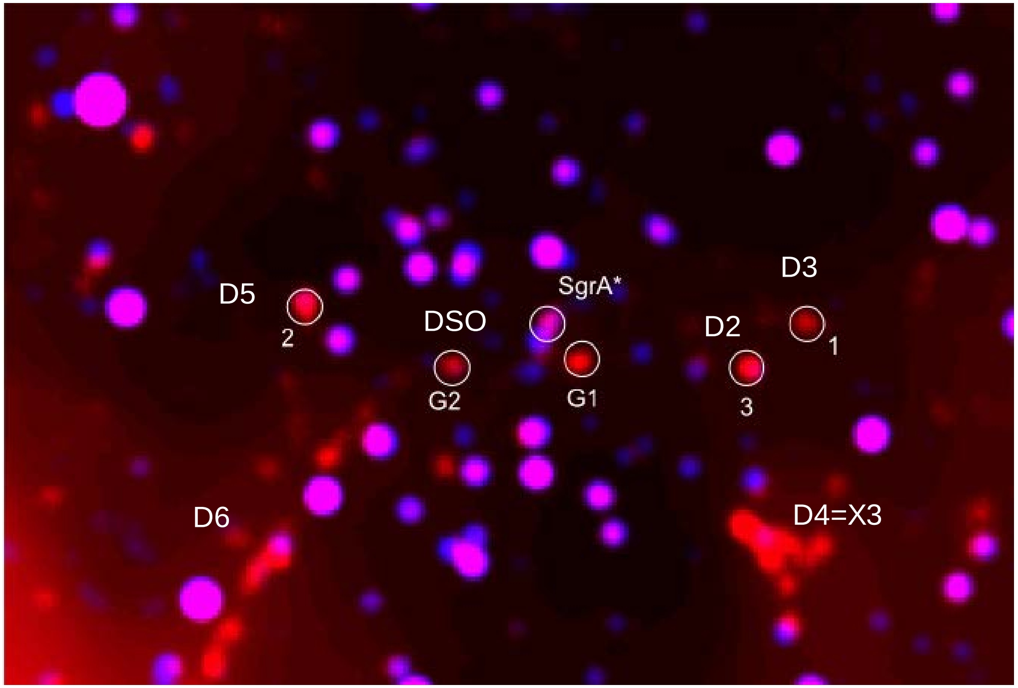
Eckart et al. 2006
Meyer et al. 2008
Zamaninasab et al. 2009/10

Reynolds et al. 2013

Upcoming violent events ?

Dusty Sources within 2” of SgrA*





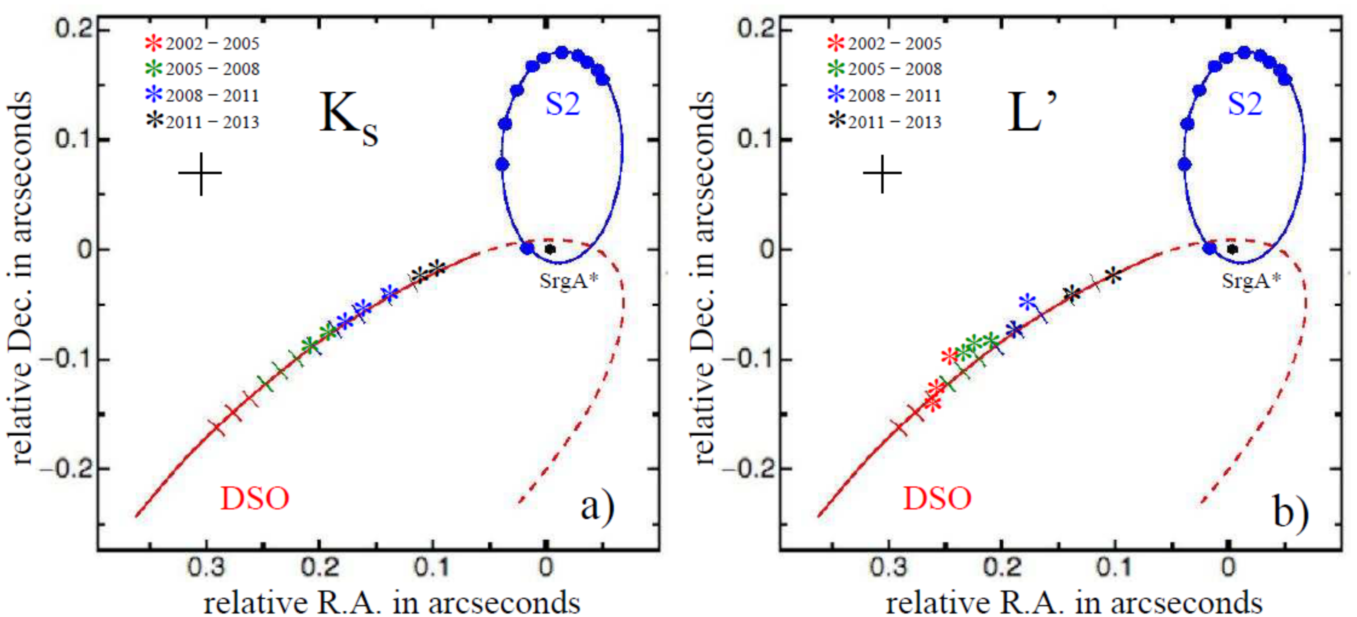
Eckart et al.
A&A 551, 18, 2013

Meyer, L.; Ghez, A. M.; Witzel, G.; et al.,
2013arXiv1312.1715M, IAU303 Symp.

A Dusty S-cluster Object is approaching SgrA*

A dusty object that can be identified with a star or a pure dust cloud
Is approaching the Black Hole SgrA* at the
Center of the Milky Way (Gillessen et al. 2012, 2013, Eckart et al. 2013ab).
Periapse has probably be reached in ***May/June 2014***.

An enhanced accretion activity is expected. Brighter flares may also help to gain information of the particel acceleration processes.

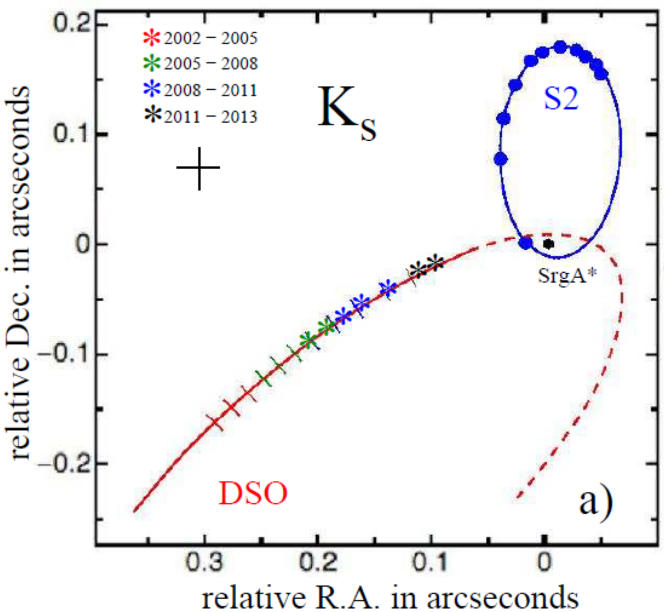


Gillessen+, Burkert+, Murray-Clay & Loeb, Eckart+ and others

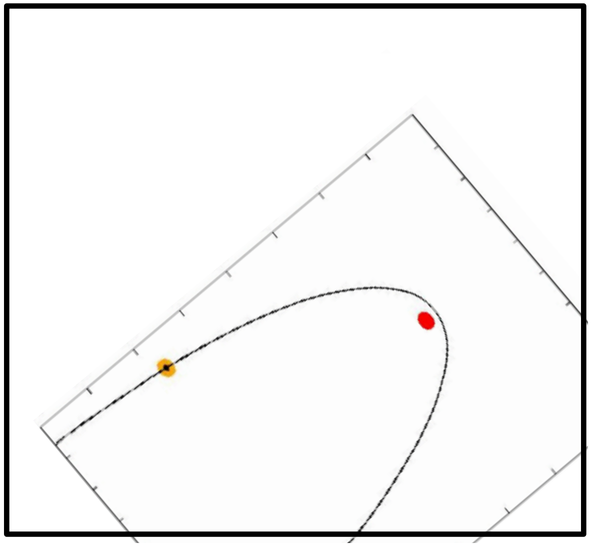
Eckart et al. 2013a

A Dusty S-cluster Object is approaching SgrA*

The K-band detection of the DSO/G2 source is important to explain expected accretion phenomena and related flux density variations of SgrA*.
It may also give a hint at what the nature of the DSO may be and how it originated.



Eckart et al. 2012



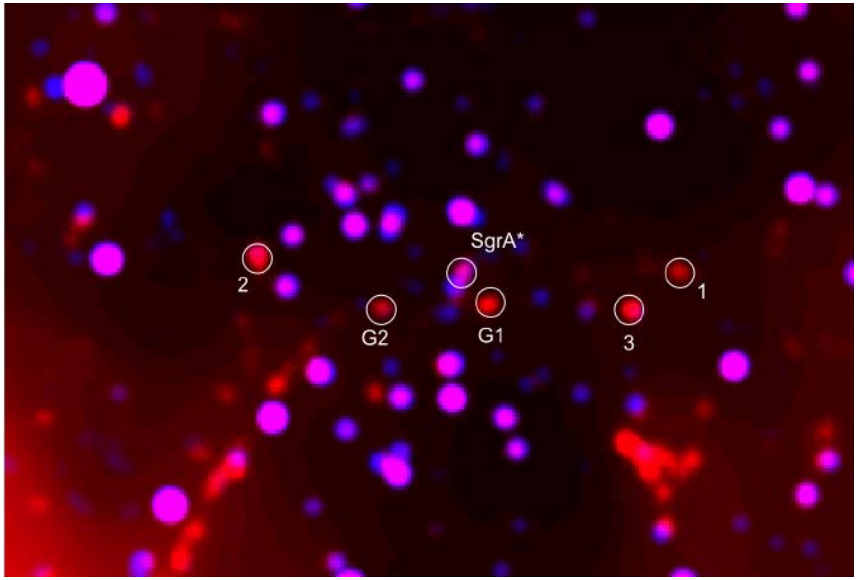
Zajacek, Karas, Eckart 2013

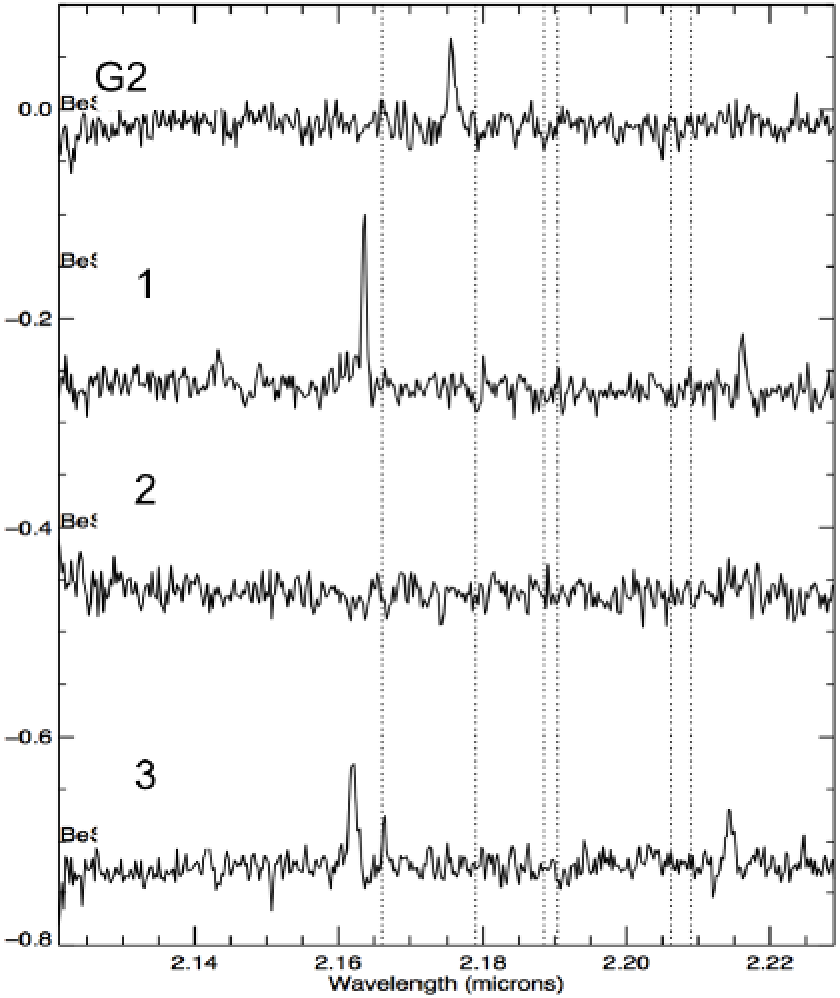
Gillessen+, Burkert+, Murray-Clay & Loeb, Eckart+ and others

Dust-enshrouded star near supermassive black hole: predictions for high-eccentricity passages near low-luminosity galactic nuclei

Current situation in the NIR and submm domain

Other Dusty S-cluster Objects close to SgrA*

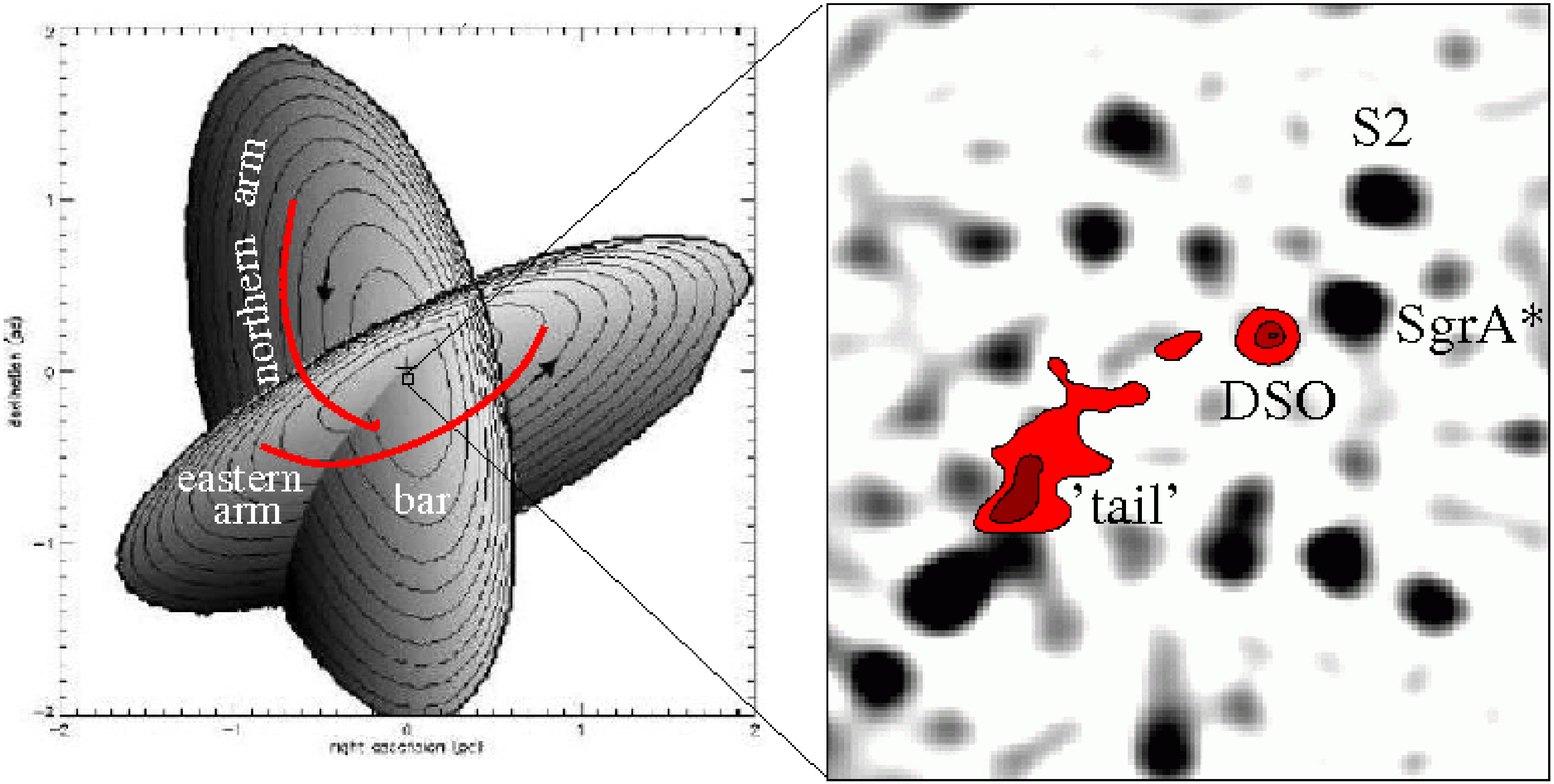




Corresponding spectra. The vertical dashed lines mark the rest wavelengths of typical stellar lines. Sources 1 and 3 show hydrogen emission with no other features, very similar to the DSO/G2 source.

Meyer, L.; Ghez, A. M.; Witzel, G.; et al., 2013arXiv1312.1715M, IAU303 Symp.

The ‘tail‘ may be part of the disk interaction zone

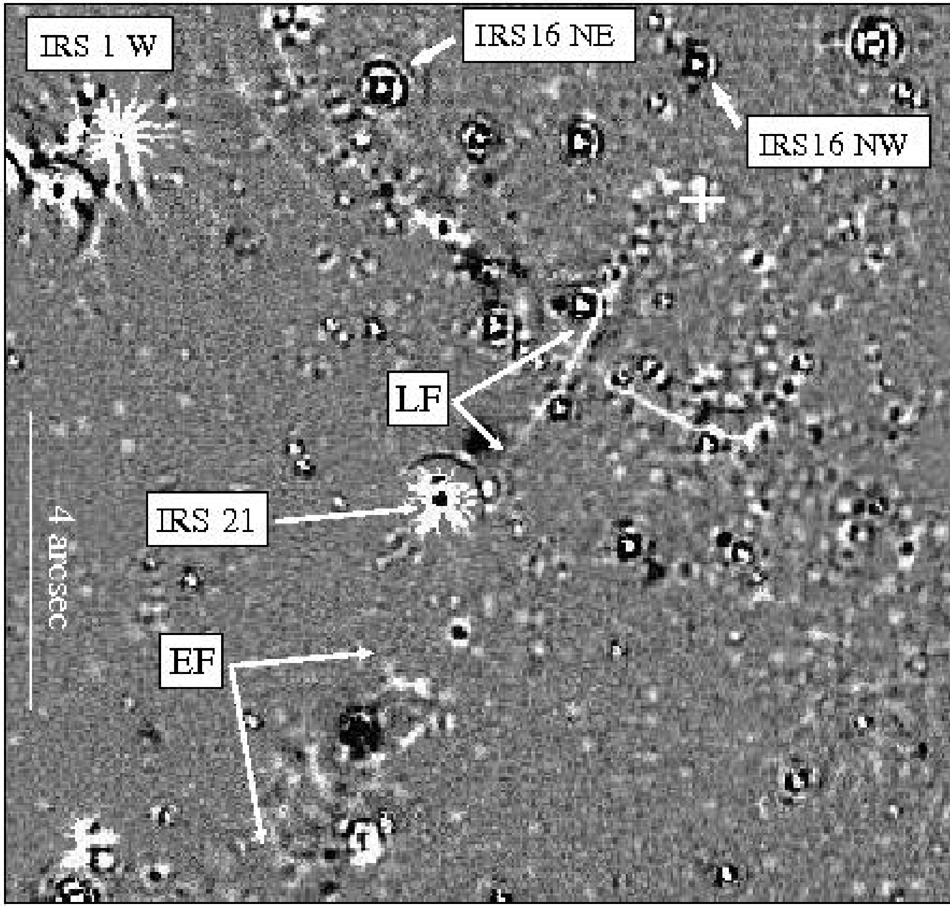


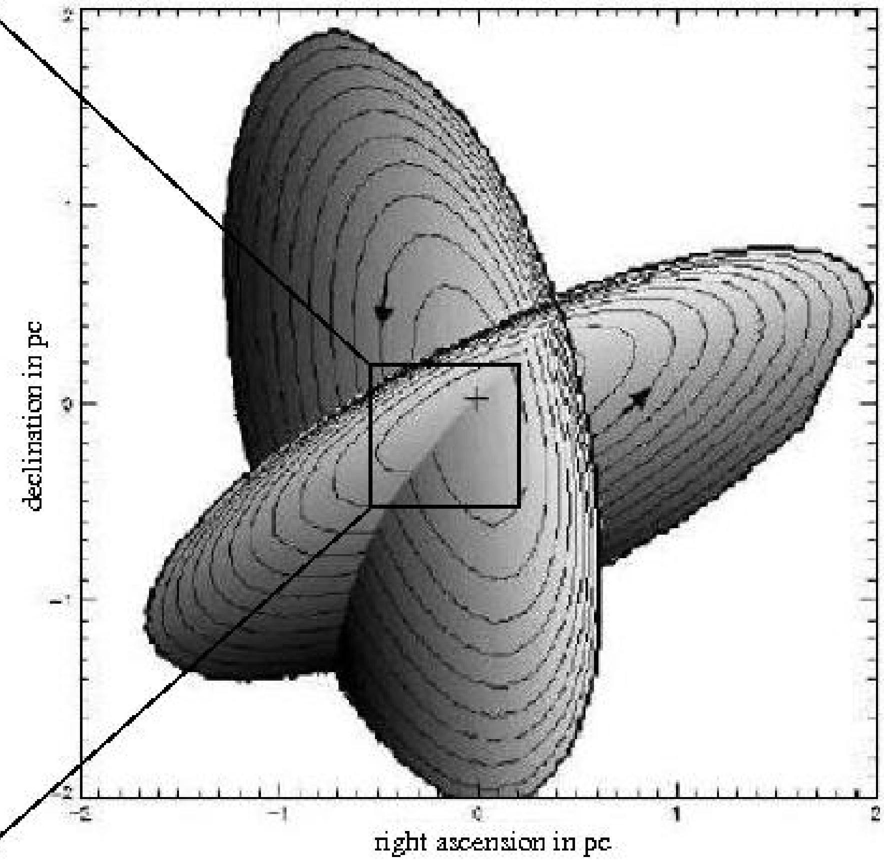
Vollmer & Duschl 2000

Eckart et al. 2013b
Gillessen et al. 2013

see Eckart et al 2013c, 2103arXiv1311.2753

The 'tail' and ‚linear feature' may be part of the disk interaction zone



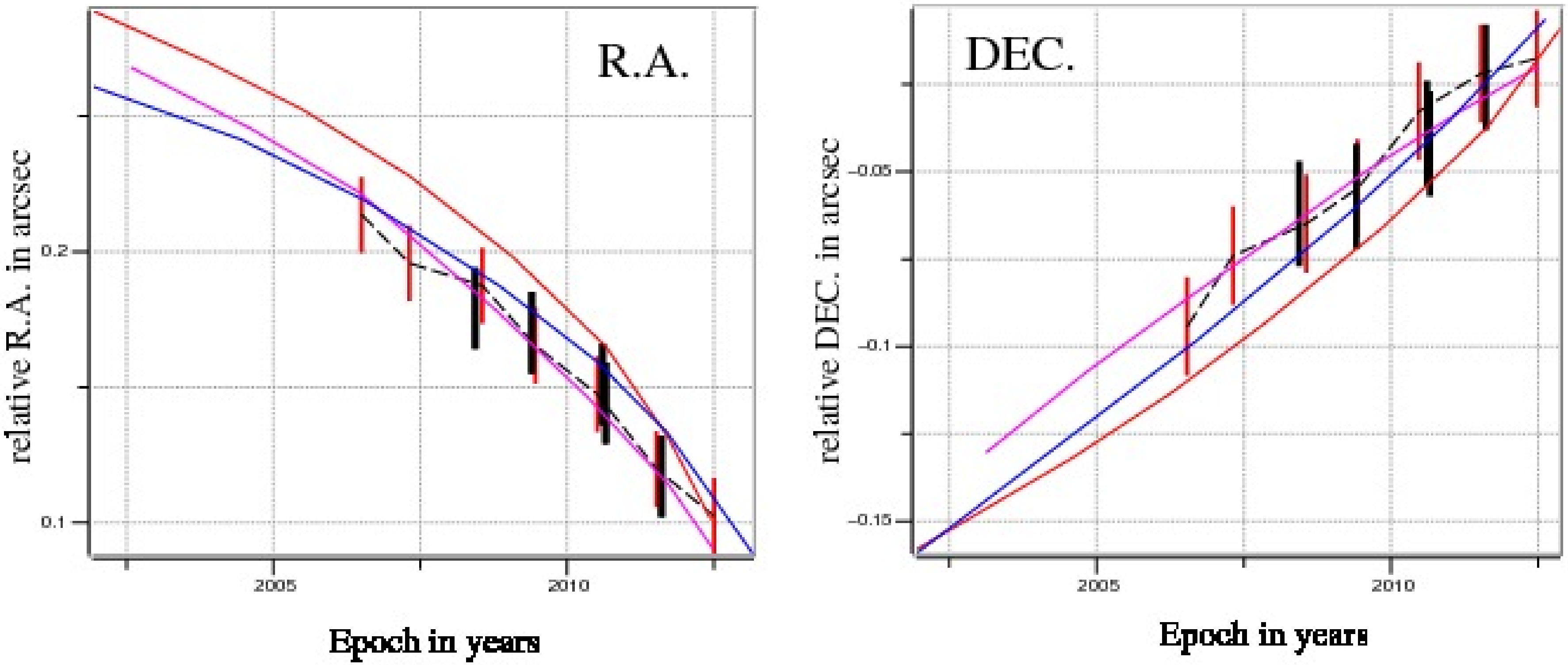


High-pass filtered L-band image
Eckart et al. 2006
with the linear feature LF crossing the northern arm
and the extended feature EF associated with the eastern arm

Vollmer & Duschl 2000

see Eckart et al 2013c, 2103arXiv1311.2753

Comparison of trajectories published for DSO/G2

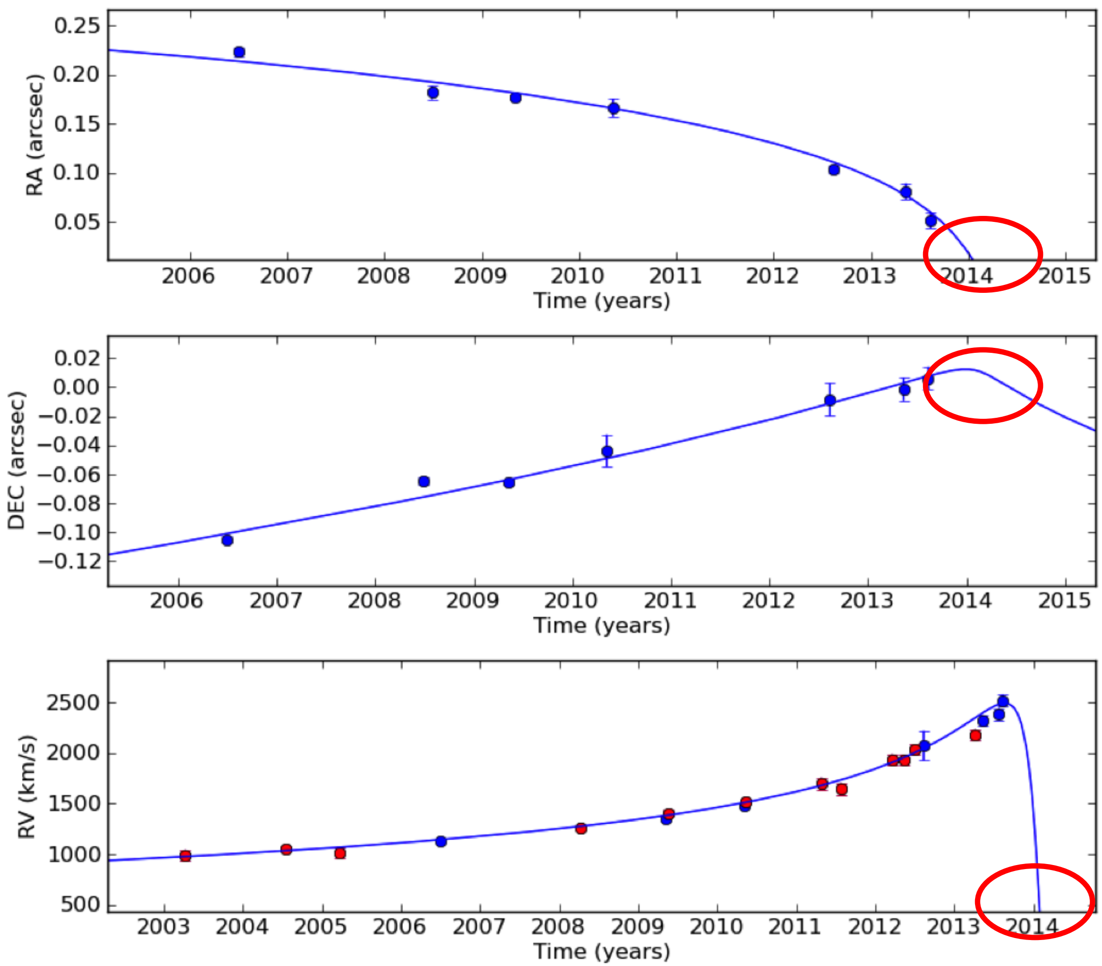


A comparison between the L'-band tracks of the DSO used by Gillessen et al. (2013) (magenta line; L'-band), Phifer et al. (2013) (blue (K'-band Brγ) and red (L'-band) lines). We also show the coordinates obtained from the Ks-band identification by Eckart et al. (2013a) using VLT NACO data (data points with red error bars connected by a black dashed line).

Data point with thick red and black error bars represent the K'-band identification based on NACO and Keck NIRC2 data.

see Eckart et al 2013b, 2103arXiv1311.2743

The DSO orbit as approaching SgrA*



Orbital solutions[1] for G2 based on Br-γ astrometry and radial v

Param	UCLA 2012[2]	MPE 2013[3]	**UCLA 2013**
ecc	0.981 ± 0.006	0.970 ± 0.003	0.965 ± 0.011
Incl [deg]	121 ± 3	118 ± 2	113 ± 3
Ω [deg]	56 ± 11	82 ± 4	77 ± 10
ω [deg]	88 ± 6	97 ± 2	92 ± 4
T_0 [year]	2014.21 ± 0.14	2014.25 ± 0.06	2014.21 ± 0.13
P [years]	276 ± 111	391 ± 66	264 ± 139

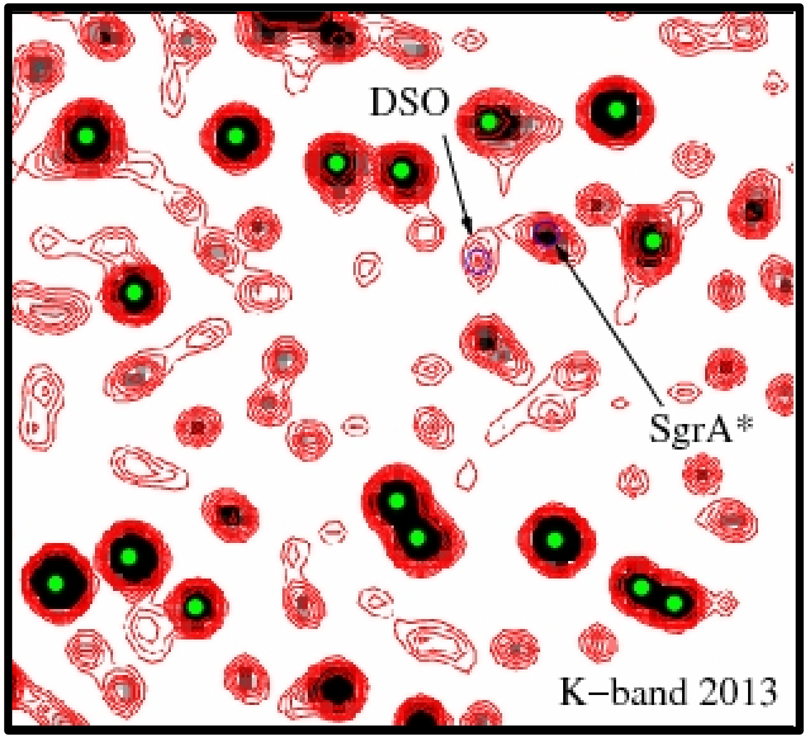
Meyer, L.; Ghez, A. M.; Witzel, G.; et al., 2013arXiv1312.1715M, IAU303 Symp.

2013 Ks-band DSO identification in VLT

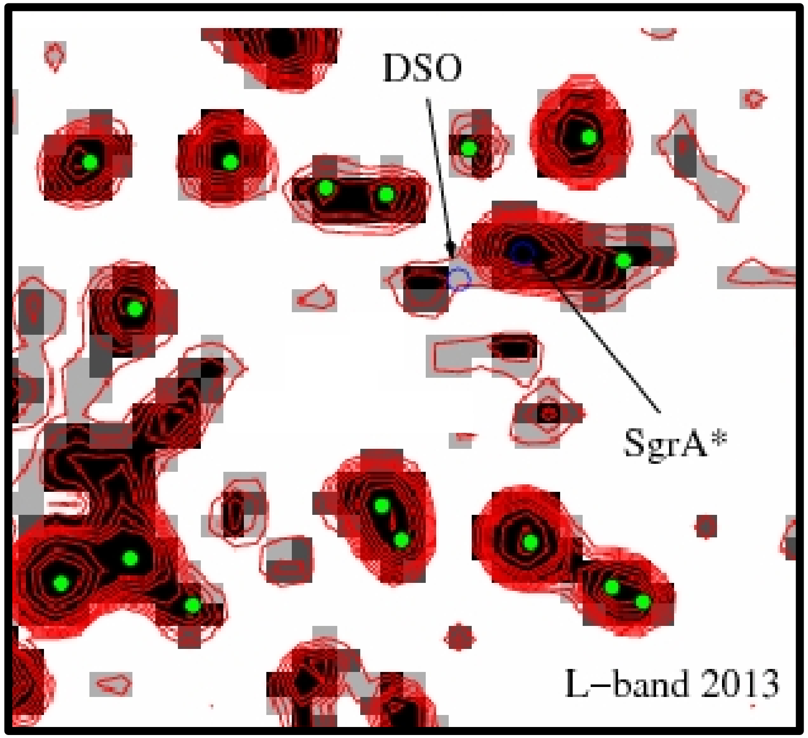
VLT UT4 NACO June/Sept 2013

~2“x 2“ field

Ks-band 2013

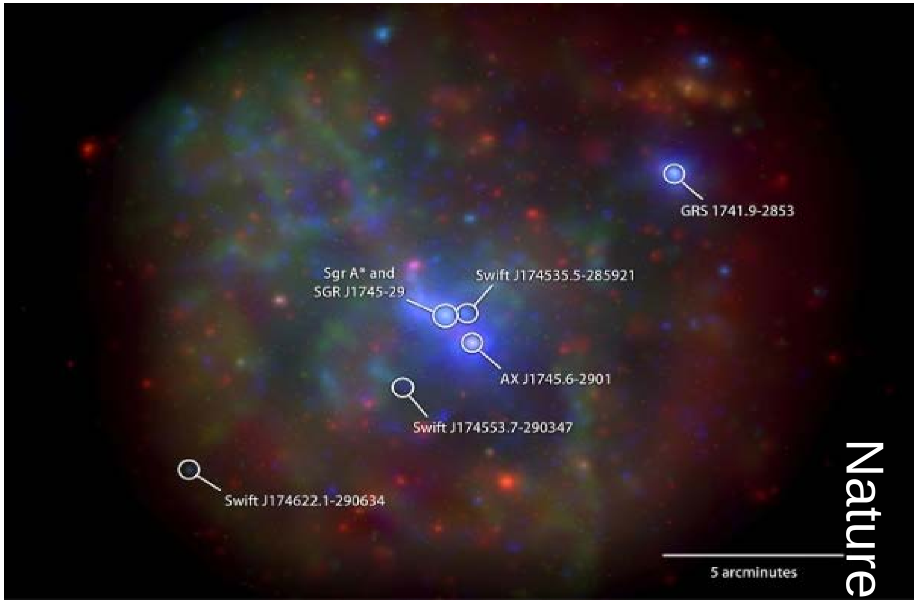


L-band 2013



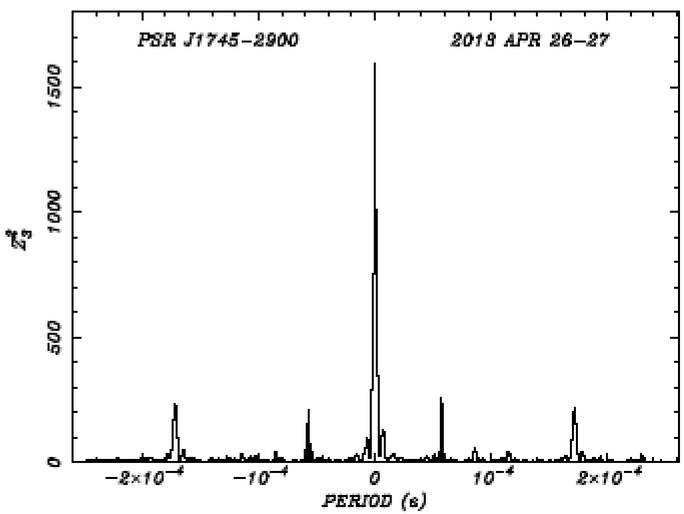
see also Gillessens 2013b

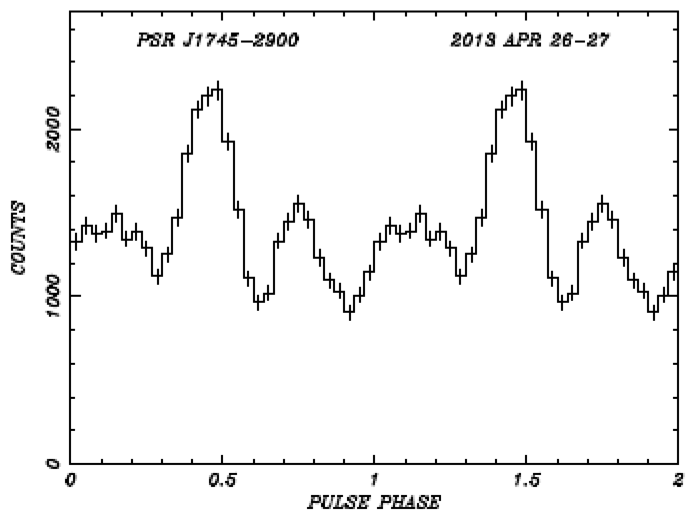
NuSTAR finds Magnetar close to SgrA*



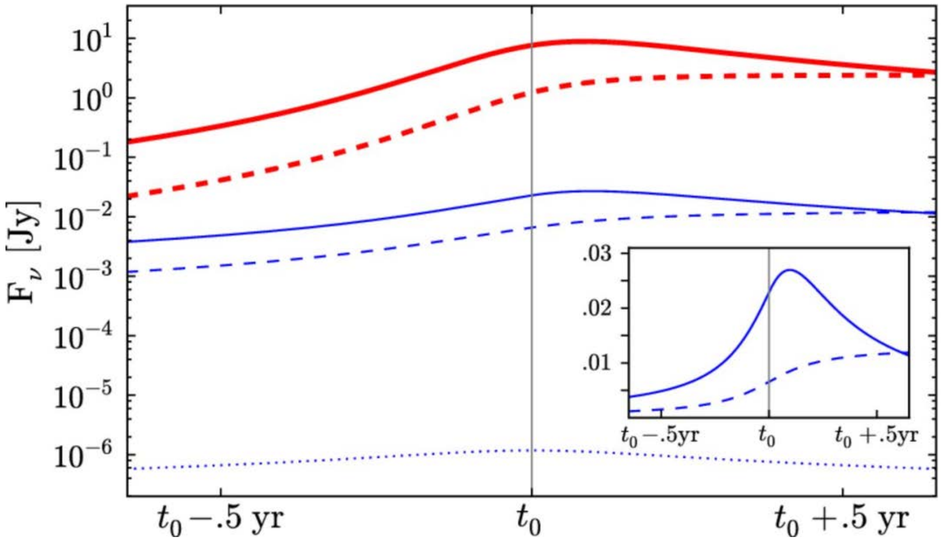
Magnetar SGR J1745-29
a few arcsec away from SgrA*
3.75s period
3.5x10^23 ergs/s luminosity
Spin down power
d/dt E~5x10^33 erg/s

Kaya Mori et al. ApJ 2013

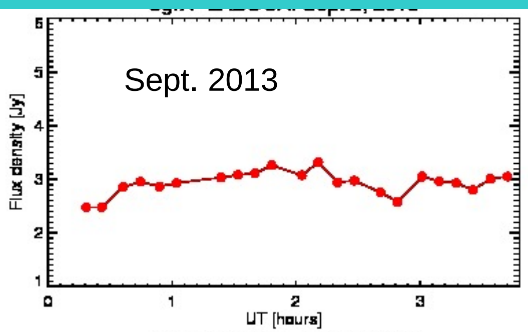


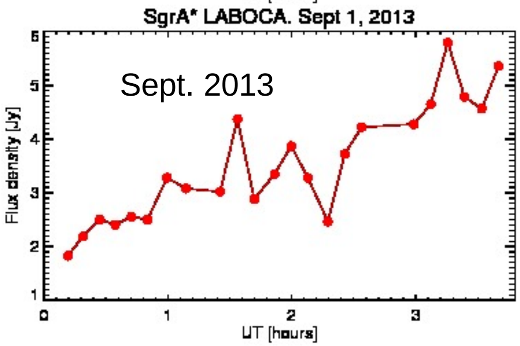


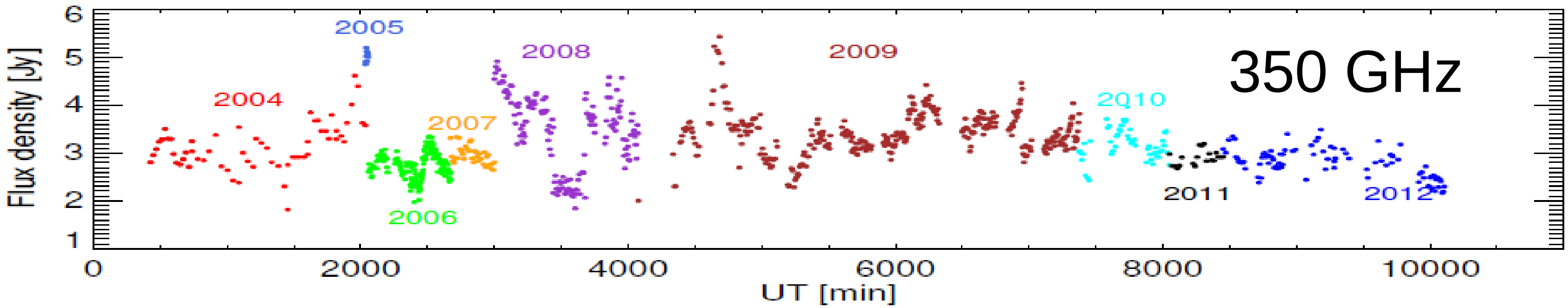
SgrA* radio flux during flyby of the DSO



Crumley & Kumar 2013







Decrease in bow-shock area by 2 orders of magnitude results in similar decrease of prevoiously predicted radio flux of 1-20 Jy i.e.: ***rather 0.01-0.2 Jy***

Crumley & Kumar 2013 MNRAS.tmp.2355C

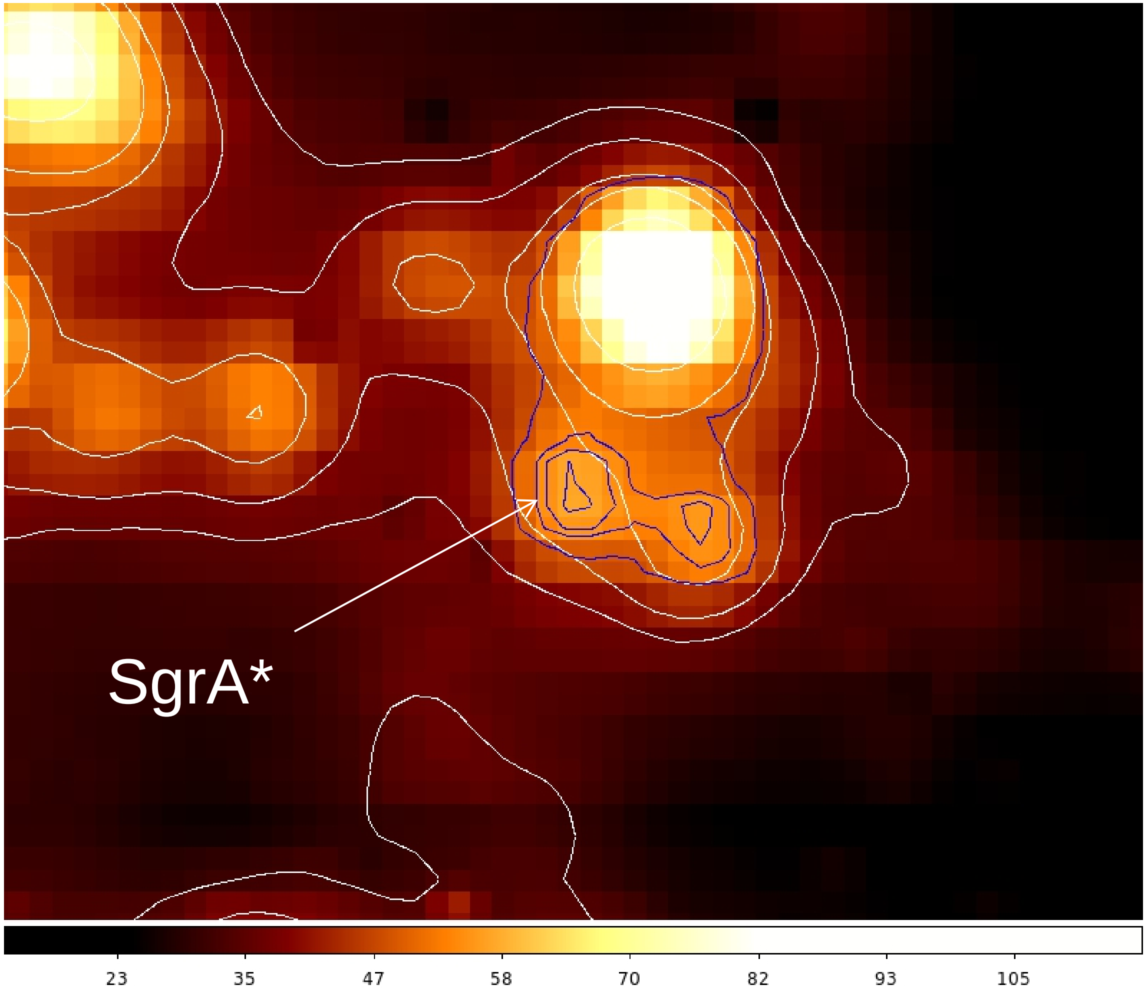
1-20 Jy predicted by Narayan et al. 2012 Sadowski et al. 2013

2014 Ks-band DSO identification at the VLT

VLT UT4 SINFONI March/April 2014

~0.6“x0.5“ field

Ks-band 2014



Detection of weak flares of SgrA* - fully compatible with known flare statistics (Witzel et al. 2012).

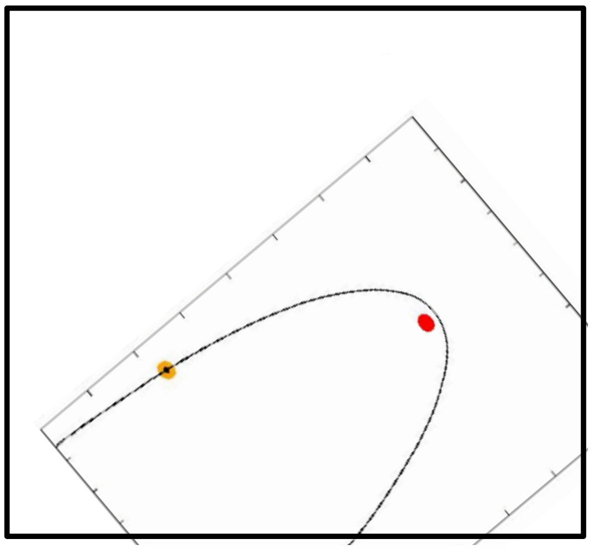
Detection of Galactic Center Source G2 at 3.8 micron during Periapse Passage Around the Central Black Hole

ATel #6110;

May 2014; 16:11

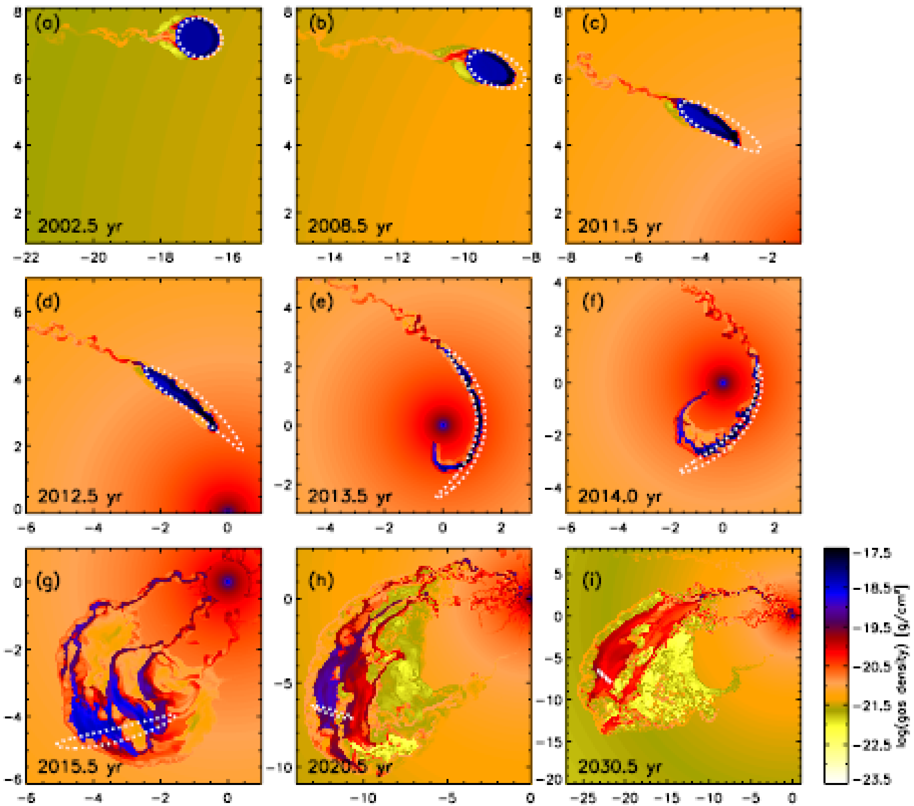
DSO still compact and not fully disintegrated
Most likely it harbours a star

DSO passing SgrA*



Zajacek, Karas, Eckart 2013

DSO still compact and not fully disintegrated
Most likely it contains a star



Burkert et al. 2012,
Schartmann et al. 2012

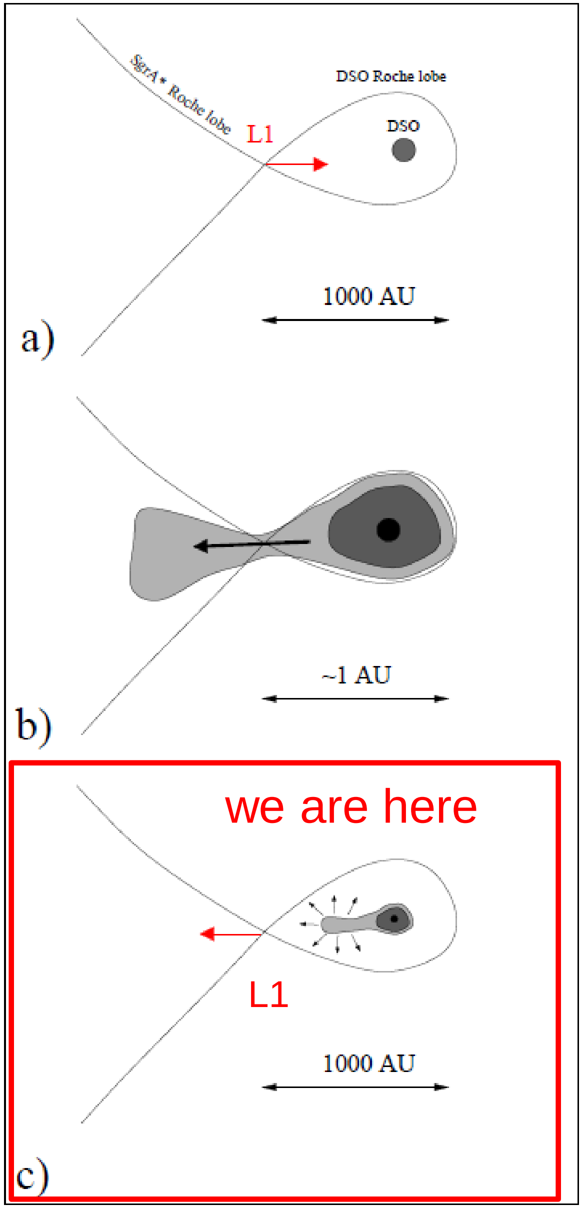


Fig. 16. Sketch of the relative position and motion of the Lagrange point L1 and the DSO.

Eckart et al. 2012

DSO Accretion in 2013/14 ?

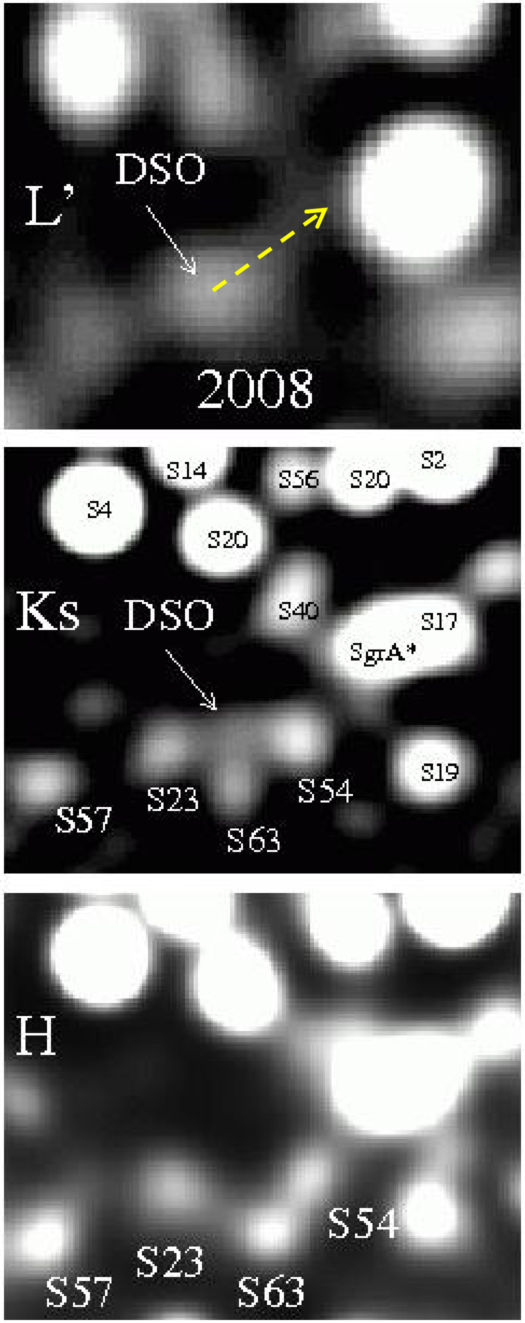
The presence of a star may have a influence on the accretion activity.

(Schartmann + 2012; Burkert + 2012)

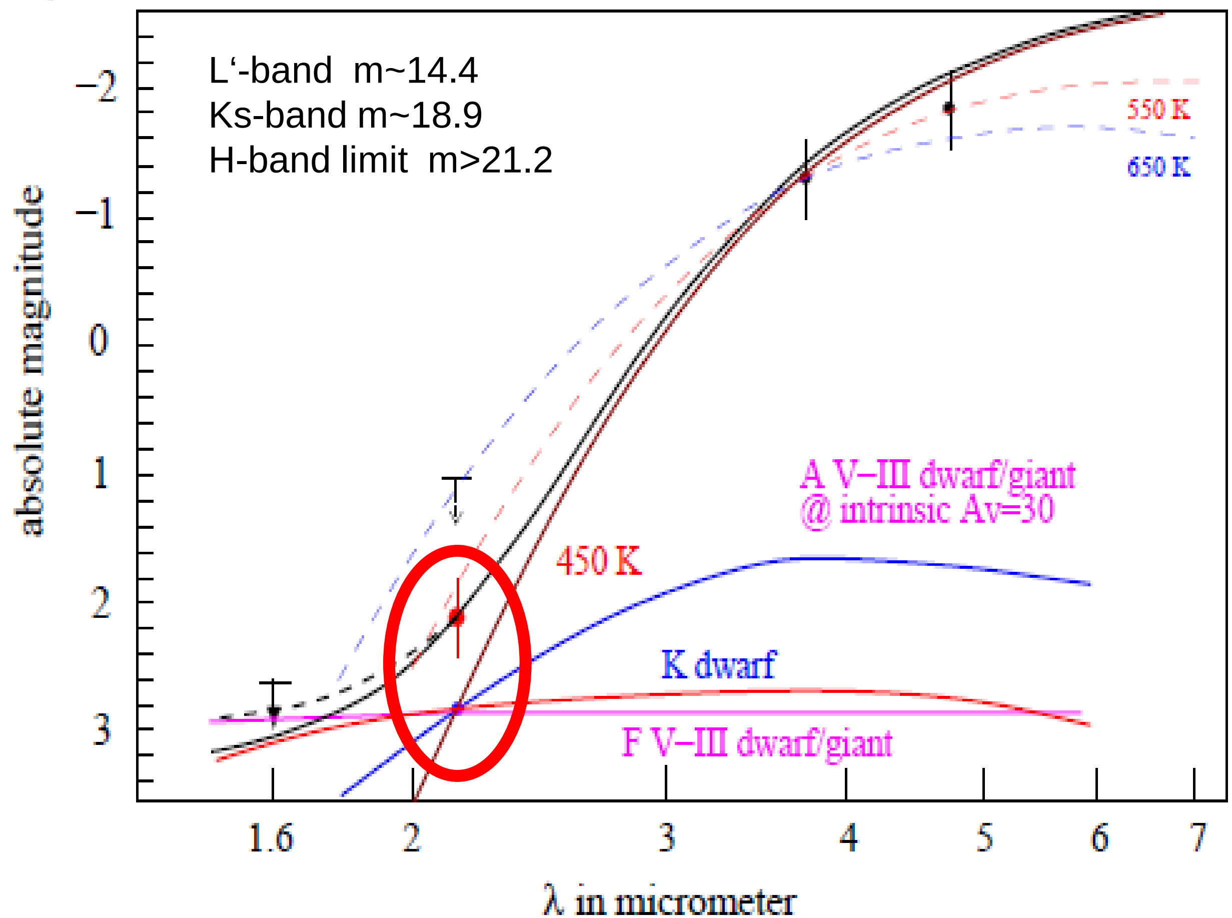
The MIR continuum emission
Is due to a compact object
(<0.1“), while the
Brγ line flux (plus disputed tail)
is extended over 0.2“
(Gillessen + 2012)

Interpretation of the
DSO K-band detection

K-band identification of the DSO



0.1'' = 4 mpc



Eckart et al. 2013a

Black body luminosities and the detection of photospheric emission imply possible stellar luminosities of up to 30 Lsol ; i.e. masses of 10-20 Msol are possible

Scenarii already discussed in Eckart et al. 2013a

Scenario I: narrow line WR star

IRS7W mk=13.1; WR2 mk=12.9; faint WR mk~15.0

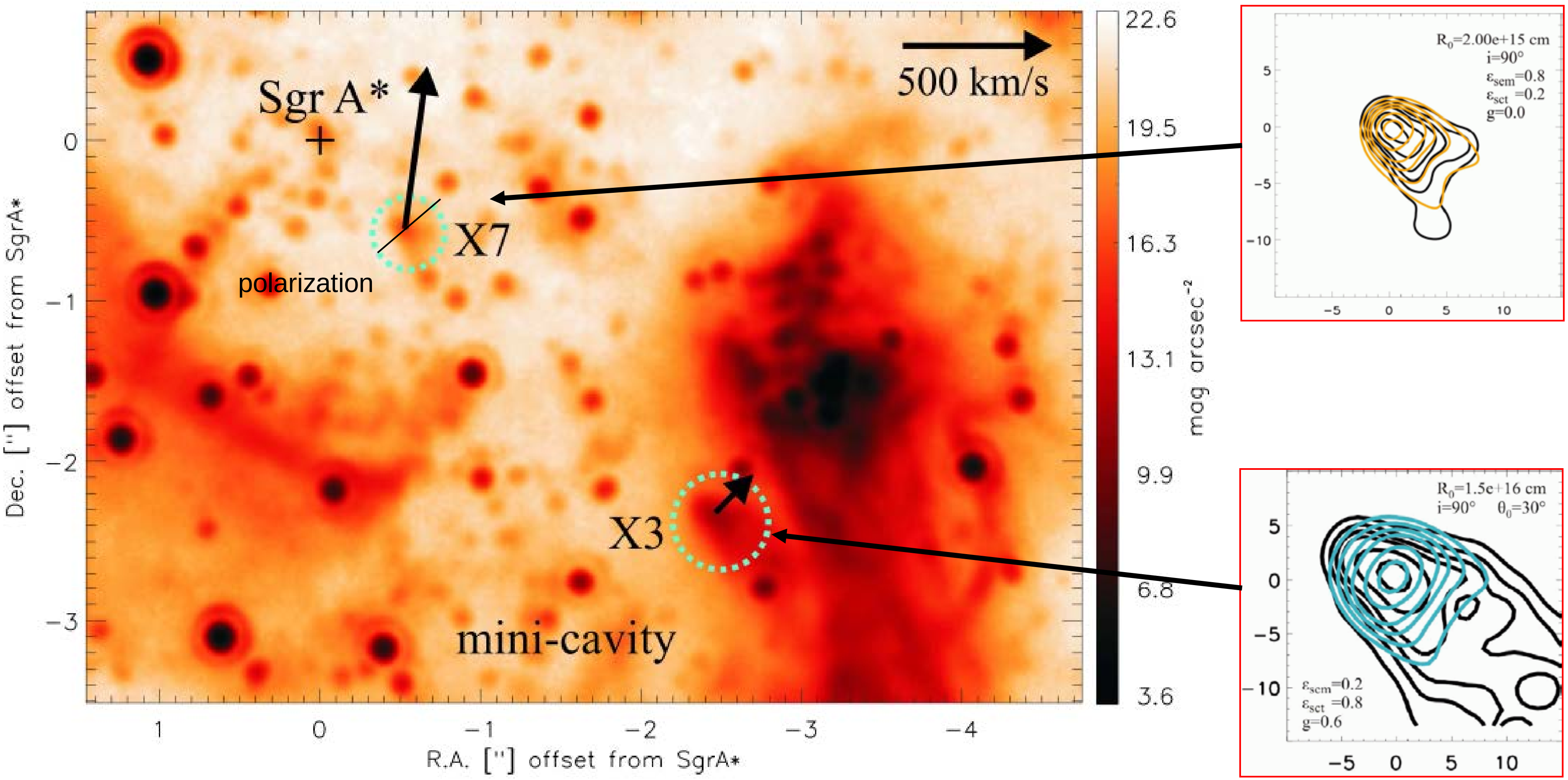
DOSA would have to be exceptionally faint; additional extinction needed

Scenario II: WNL star/OB giant (Dong, Wang & Morris, 2012)

Scenario III: young stallar source (Murray-Clay & Loeb 2011)

Scenario IV: similar to X3/X7 Muzic et al. (2010) and or progenitor
of the S-cluster stars i.e. B-stars?
low luminosity main sequence Av=0-30mag
AV-III dawrf/giant
B-type like B7-8V
FV-III dwarf/giant
K dwarf

Cometary Sources: Shaped by a wind from SgrA*?

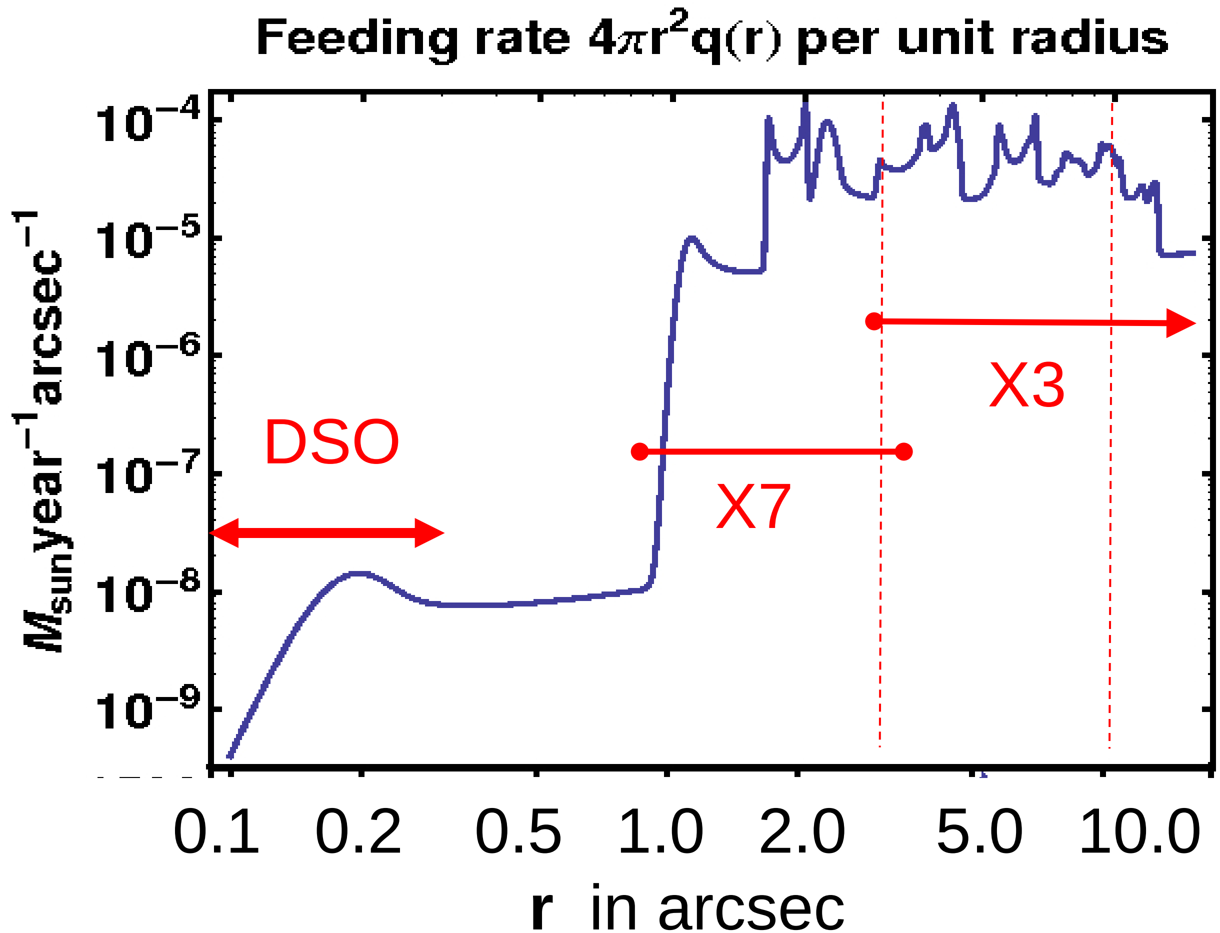


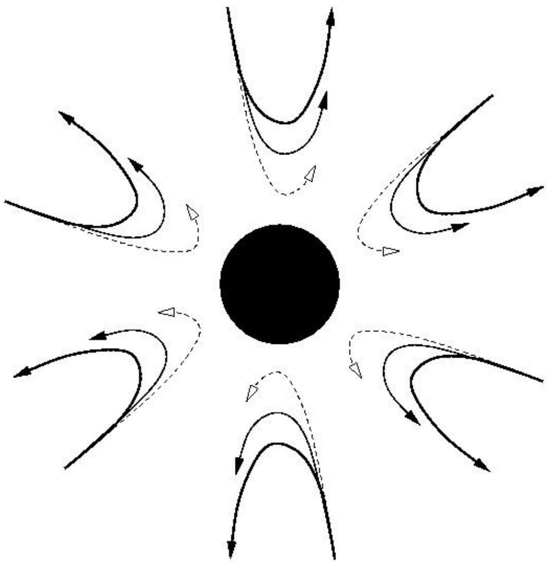
X7 polarized with 30% at PA -34+-10
Mie → bow-shock symmetry along PA 56+-10
includes direction towards SgrA*

Besides the mini-cavity – X3 and X7 are the strongest indication for a fast wind from SgrA*!

Muzic, Eckart, Schödel et al. 2007, 2010

Accretion onto SgrA*





radius dependent accretion

Mass input into the feeding region around the BH. Using square averaged wind velocities feeding is averaged over stellar orbits. Each wiggle represents a turning point of a single orbit. Only a few stars may feed matter within 0.8".

see Eckart et al 2013c, 2103arXiv1311.2753

Shcherbakov & Baganoff ApJ, 2010

Modeling Approach

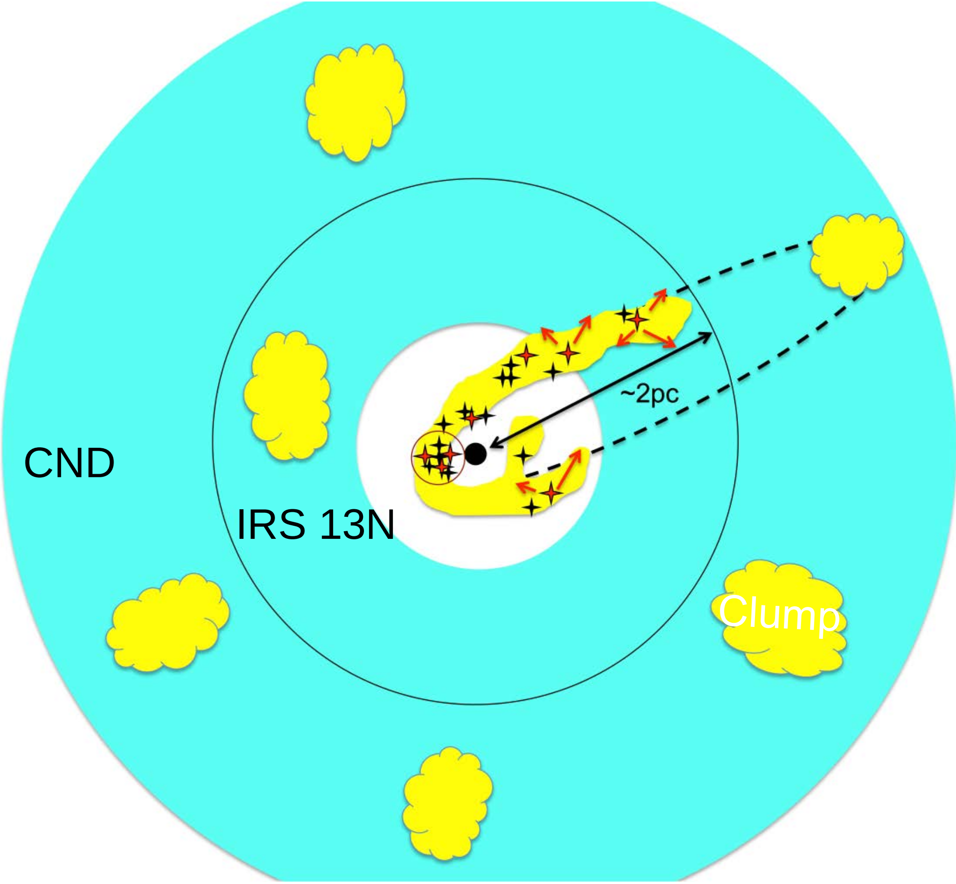
100 Msun molecular clump,
0.2 pc radius,

Test with 10 & 50 Kelvin,
isothermal gas

Timescales:
clump free fall time ~ 10^5 yr
CND orbital period ~ 10^5 yr

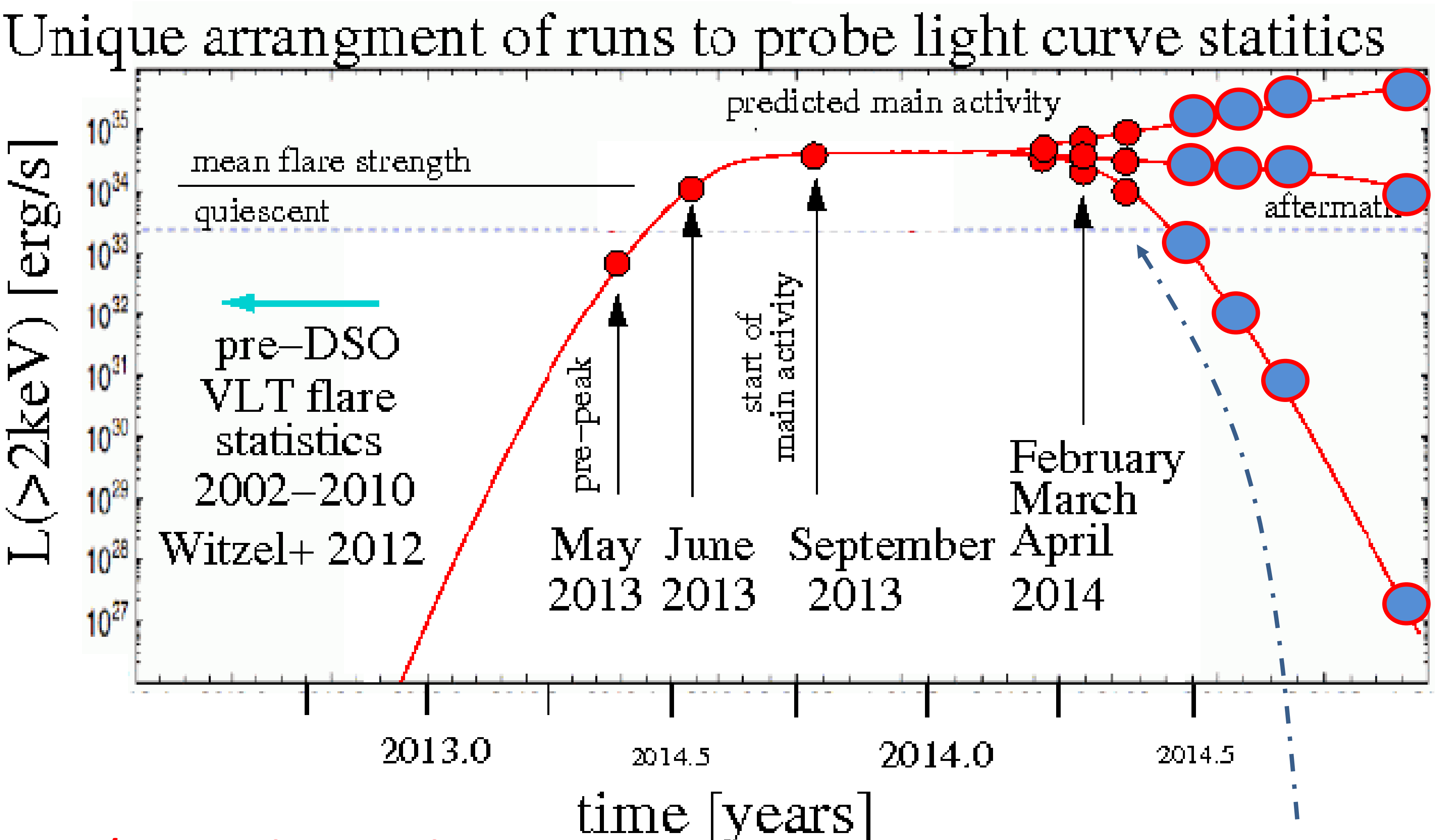
Semi-major axis=1.8 pc →
orbital period ~10^5 yr,

two Orbits:
peri-center~0.1 pc → ecc.= 0.95
peri-center~0.9 pc → ecc.= 0.5



**Behrang Jalali, I. Pelupessy, A. Eckart, S. Portegies Zwart,
N. Sabha, A. Borkar, J. Moultaka, 2013 submitted.**

Observing the DSO Flyby 2013/2014



2013/14 NIR sub-mm multi-wavelength run (Eckart+)

predictions: Gillessen+ Phifer+ 13

$$L = \frac{GM\dot{M}}{2r} = 2\pi r^2 \sigma T^4$$

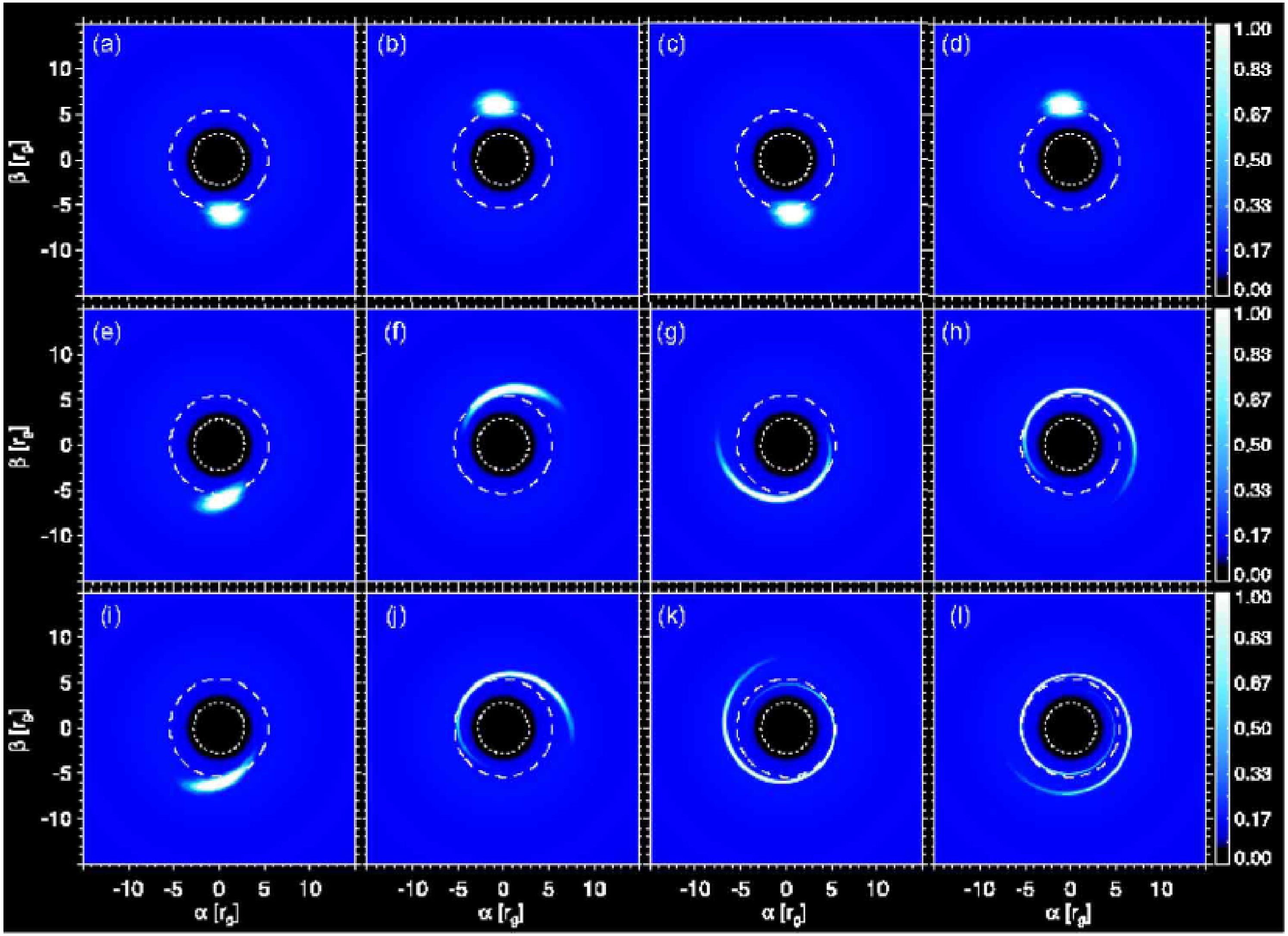
XMM
N. Grosso,
D. Porquet et al.

Spot evolution in a differentially rotating disk

face on view
i=0; a=0.5

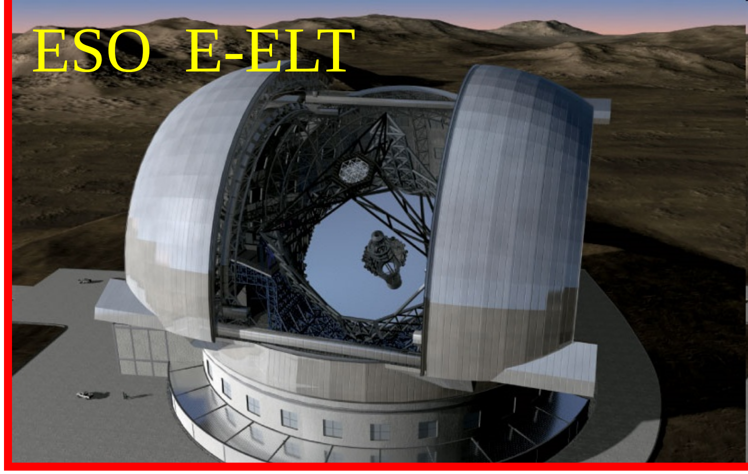
at times after
1/4T, 3/4T,
5/4T and 7/4T
(left to right).

different
degrees
of spot
shearing



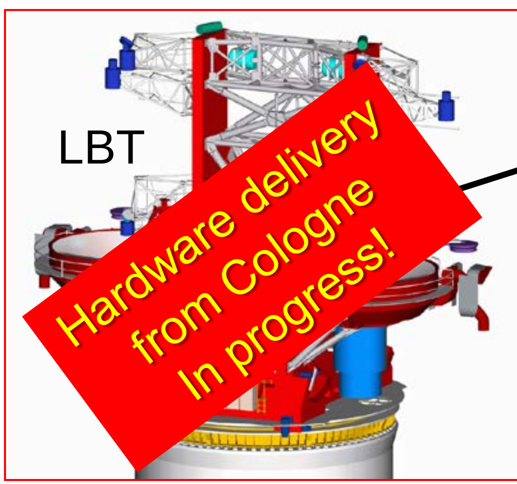
Zamaninasab et al. 2009

NL leads Euro-Team
Universitity of Cologne
studies for
METIS @ E-ELT



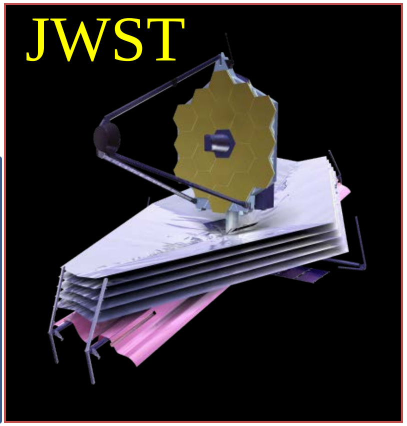
MPE, MPIA, Paris, SIM
Universitity of Cologne
participation
GRAVITY @ VLTI

The Galactic Center is a unique laboratory in which one can study signatures of strong gravity with GRAVITY



NIR Beam Combiner:
University of Cologne
MPIA, Heidelberg
Osservatorio Astrofisico di Arcetri
MPIfR Bonn

Cologne contribution to MIRI on JWST
Done!



END