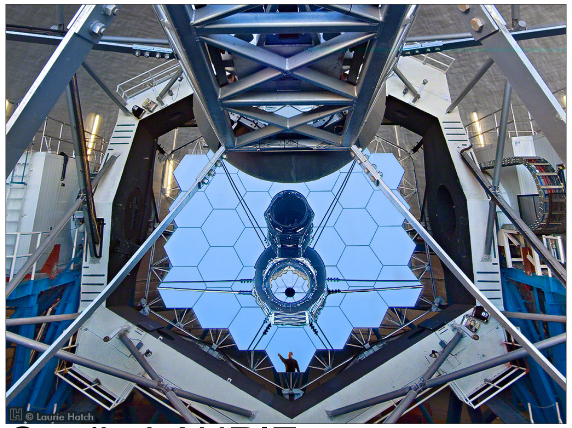
A multi-wavelength, multi-scale view of the Galactic Center

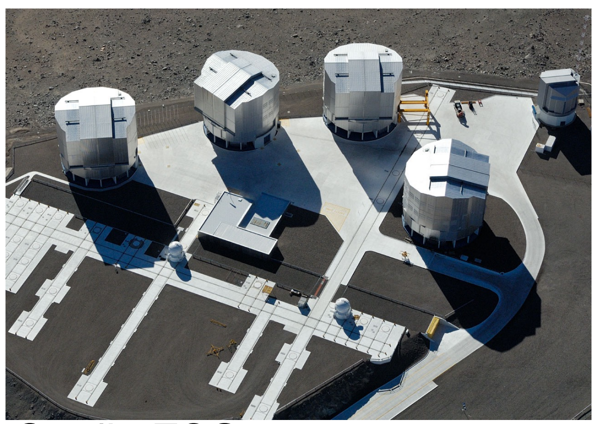
Gunther Witzel

Max Planck Institute for Radio Astronomy

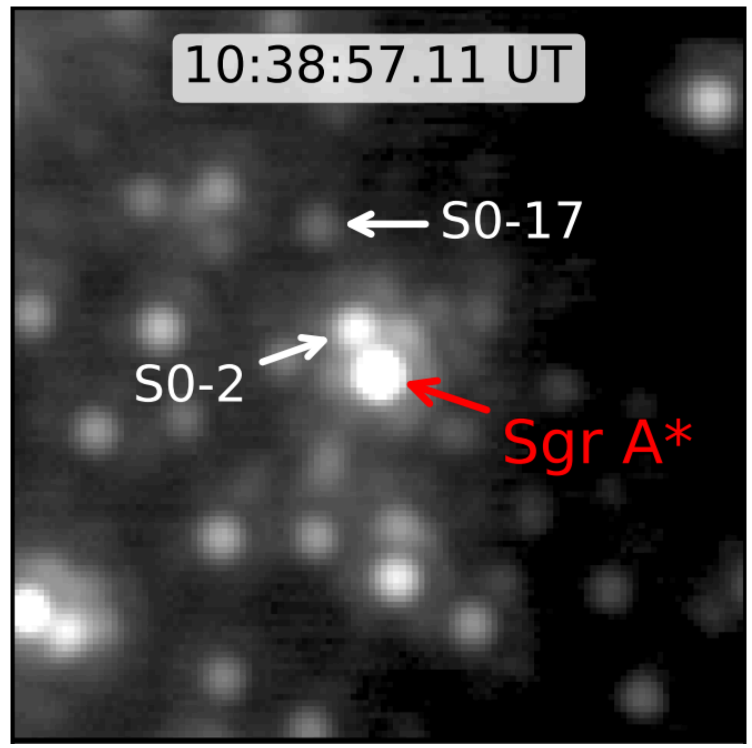
Max-Planck-Institut für Radioastronomie



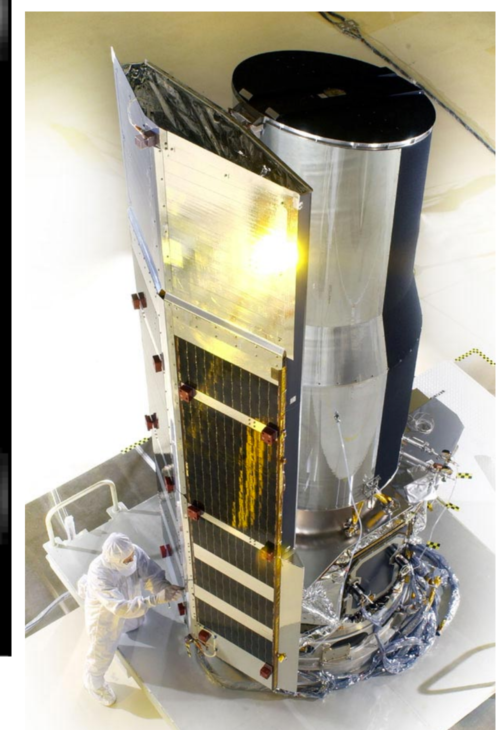
Credit: LAURIE HATCH



Credit: ESO

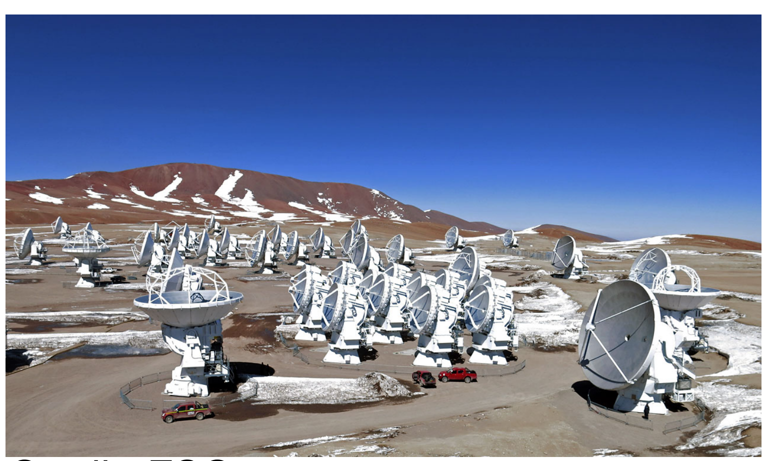


Do et al. 2019

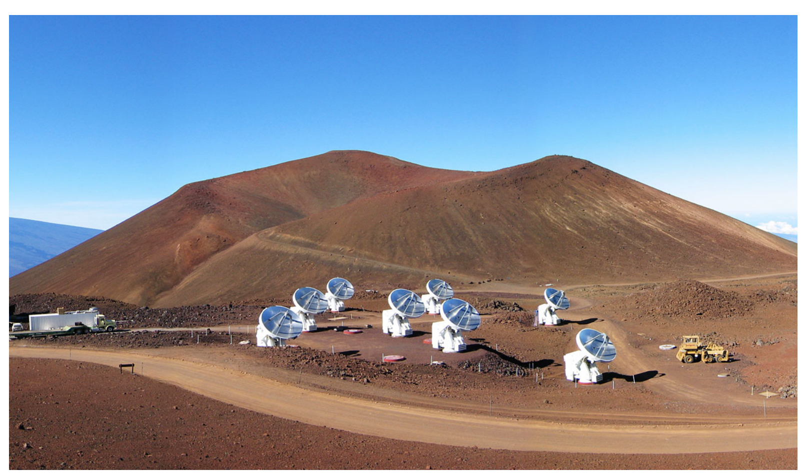


Credit: Russ Underwood

Credit: NGST



Credit: ESO



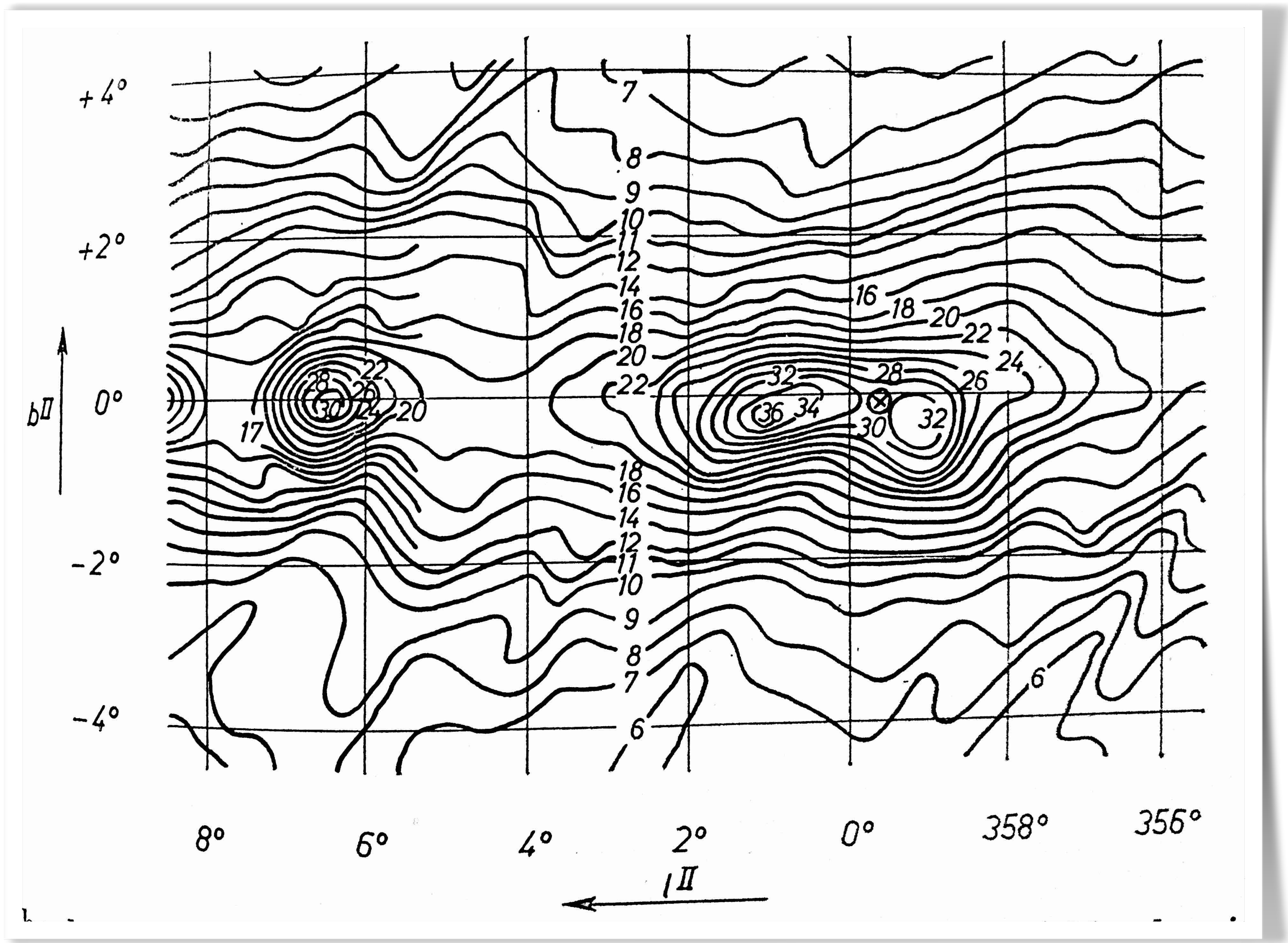
Credit: J. Weintroub

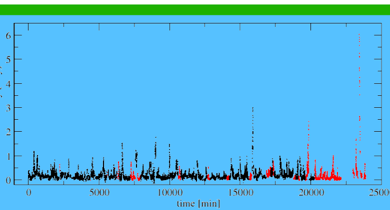
Credit: ESO

Fero10, March 2022, IRAP, Toulouse

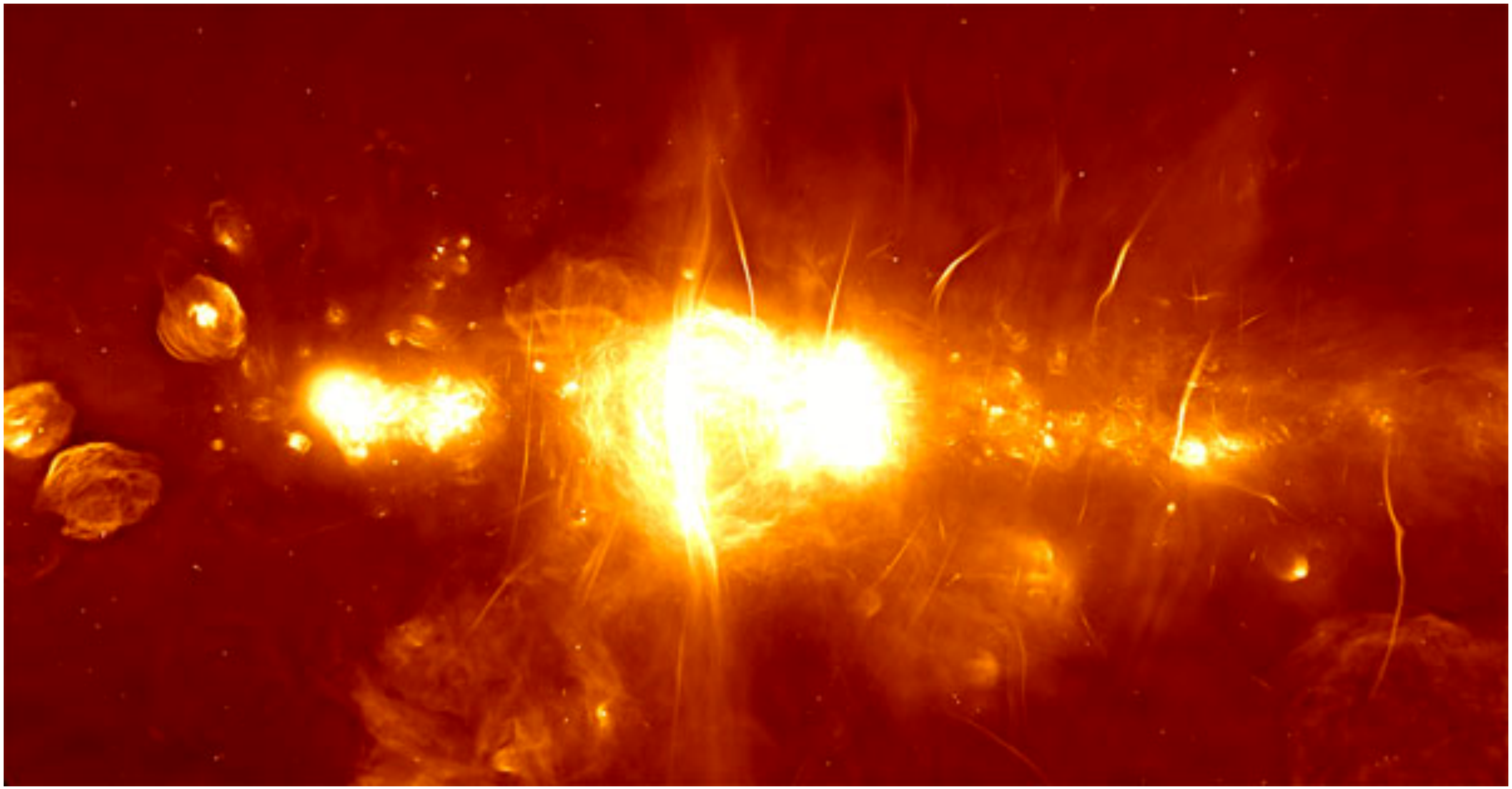
The Galactic Center

85 MHz, Mills+1956 (from Witzel+1967)



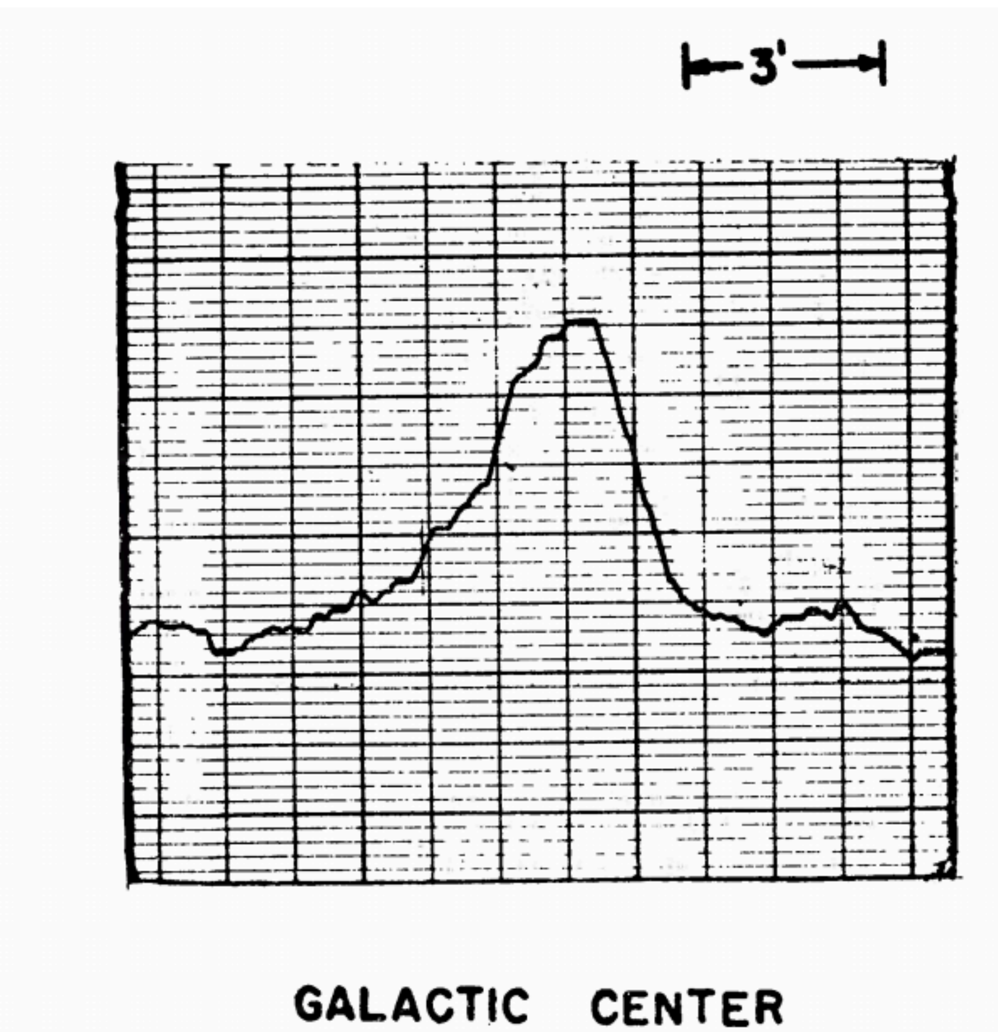



The Galactic Center



MeerKAT 900-1670 MHz, 2x1 Grad, 1000x500 Lichtjahre

The Galactic Center in the NIR: Becklin & Neugebauer 1967



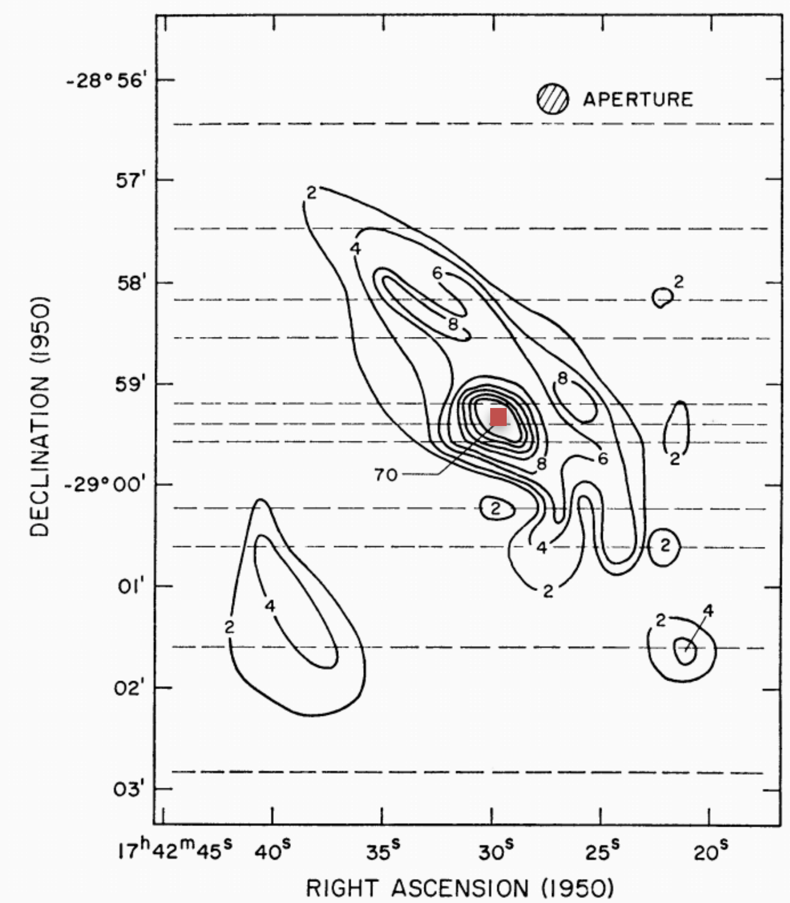
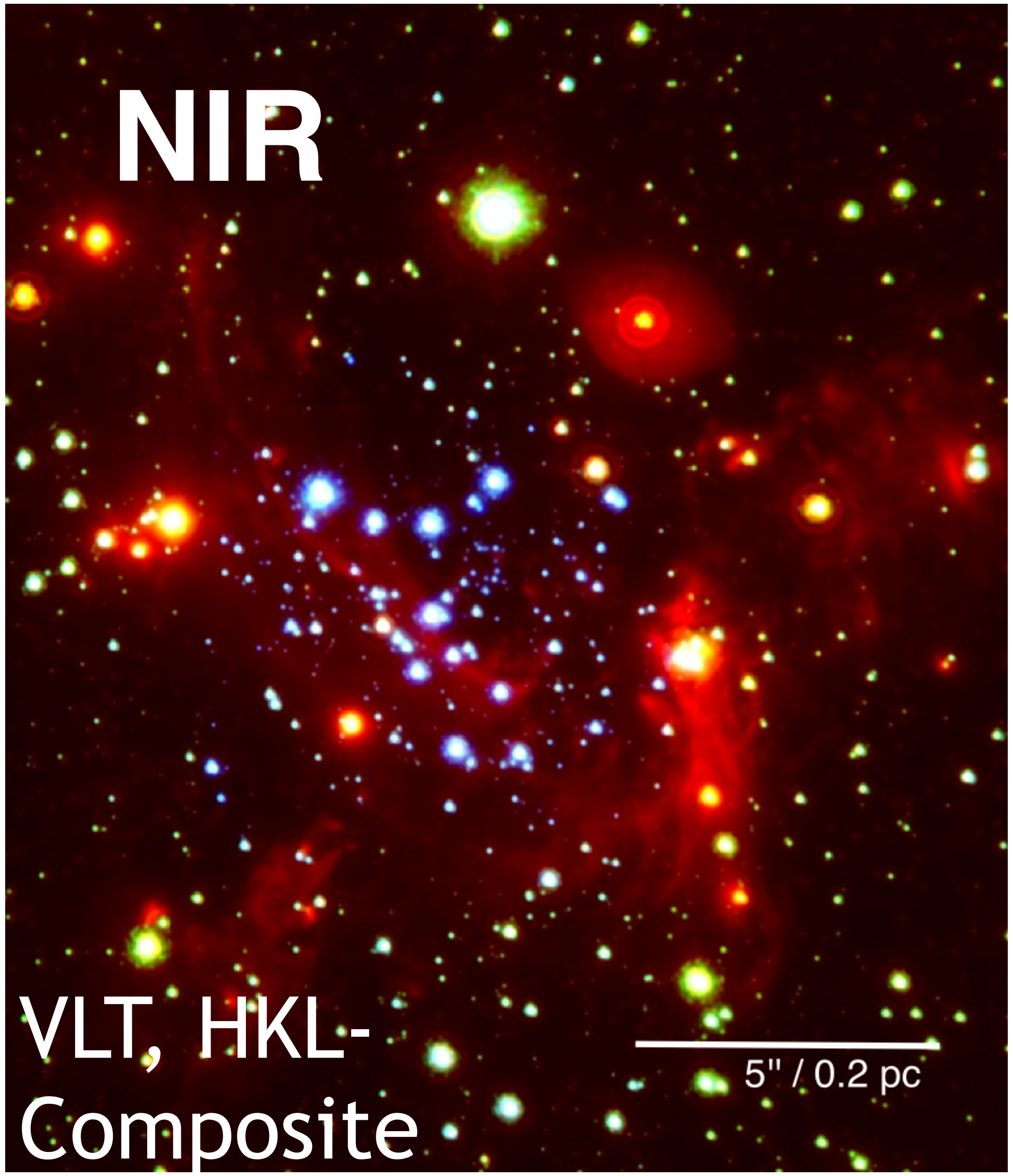
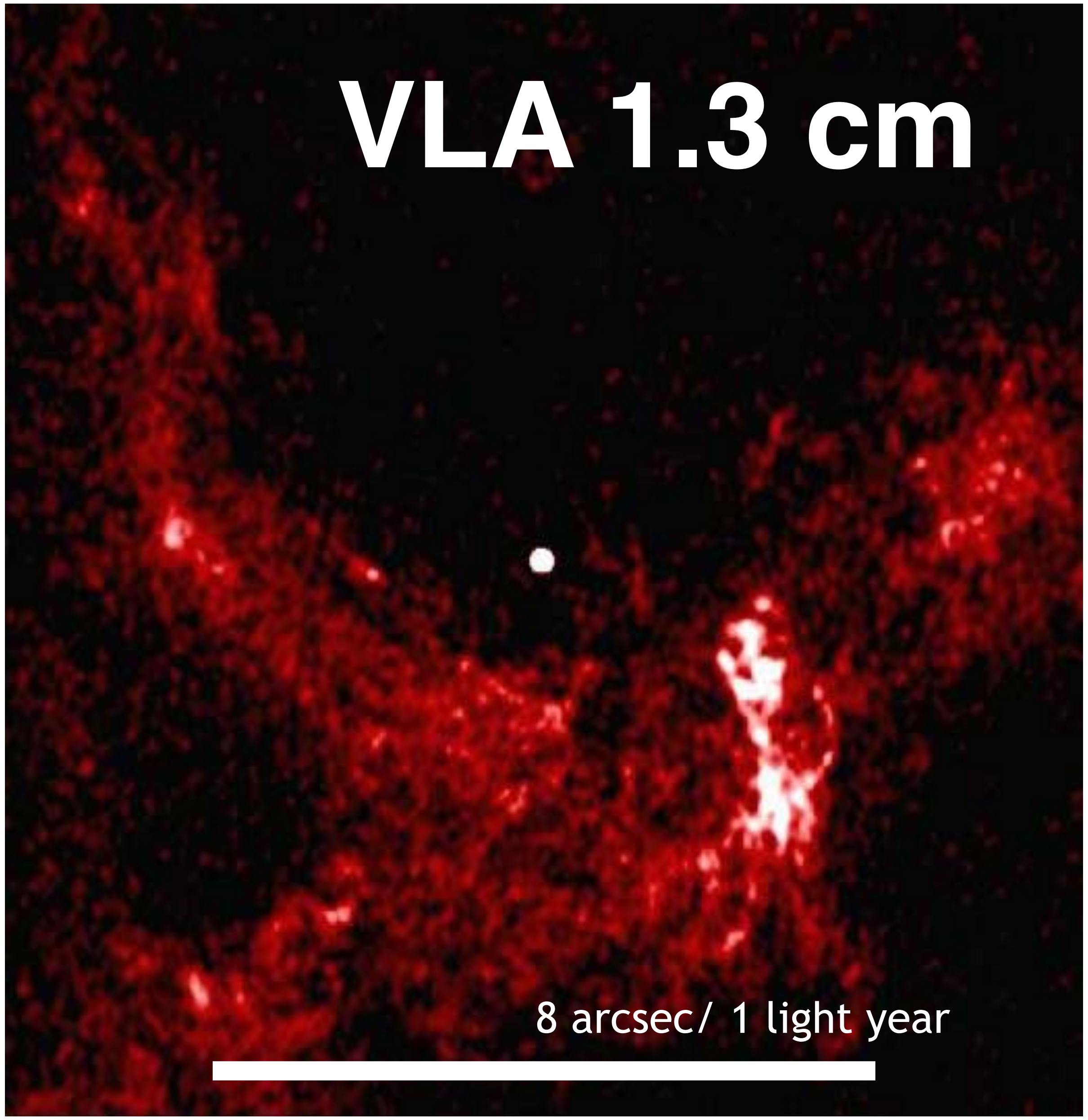


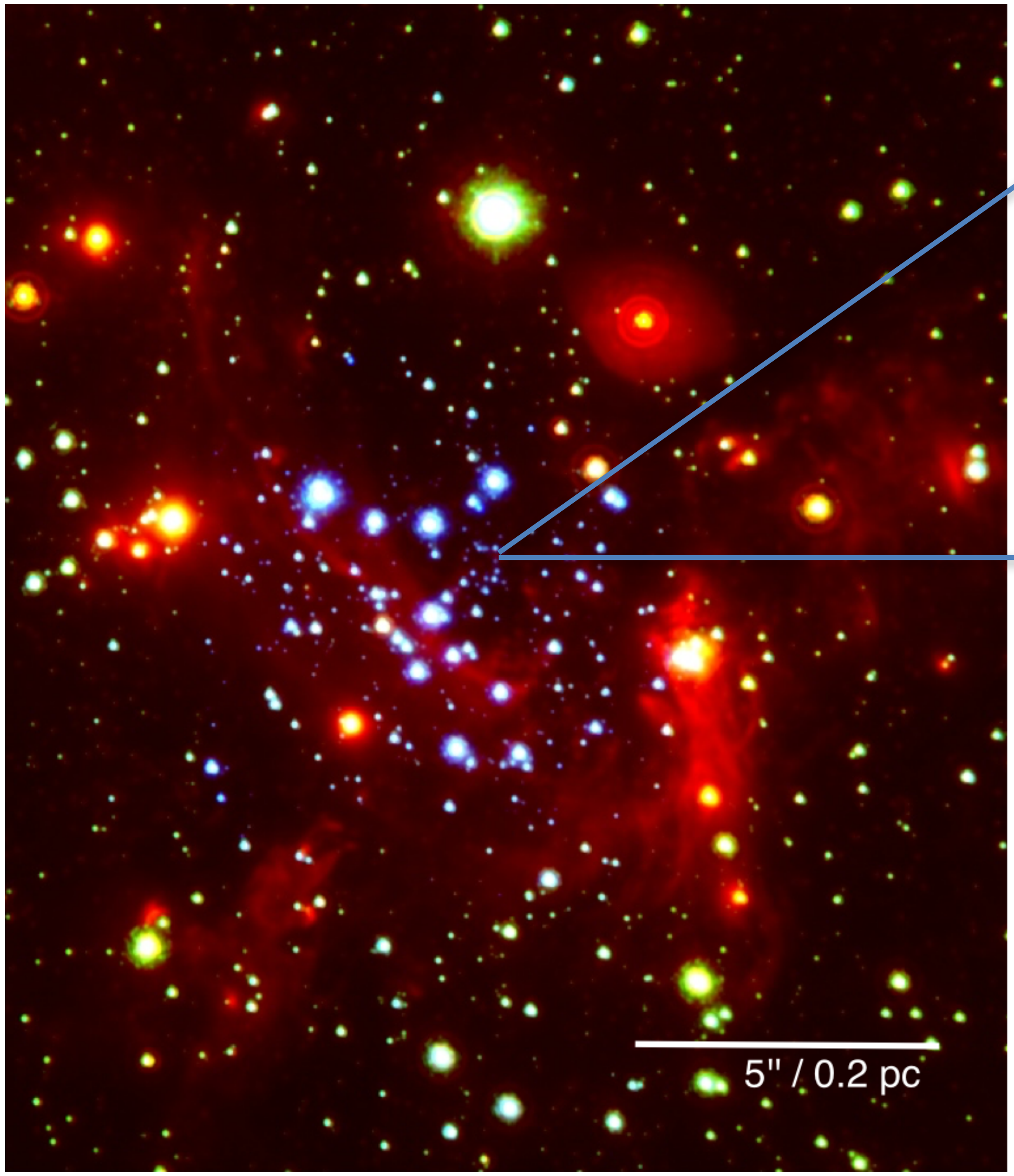
FIG. 6.—A contour map of the galactic center region at 2 2 μ taken with an aperture of 0′25 diameter is given. Contour lines are labeled in units of 1.6×10^{-19} W m^{-2} Hz^{-1} sterad^{-1} and are uncertain by about the same amount. The unlabeled contours in the center have values 10, 12, 14, and 16, respectively. The position of each scan is shown by a dashed line.

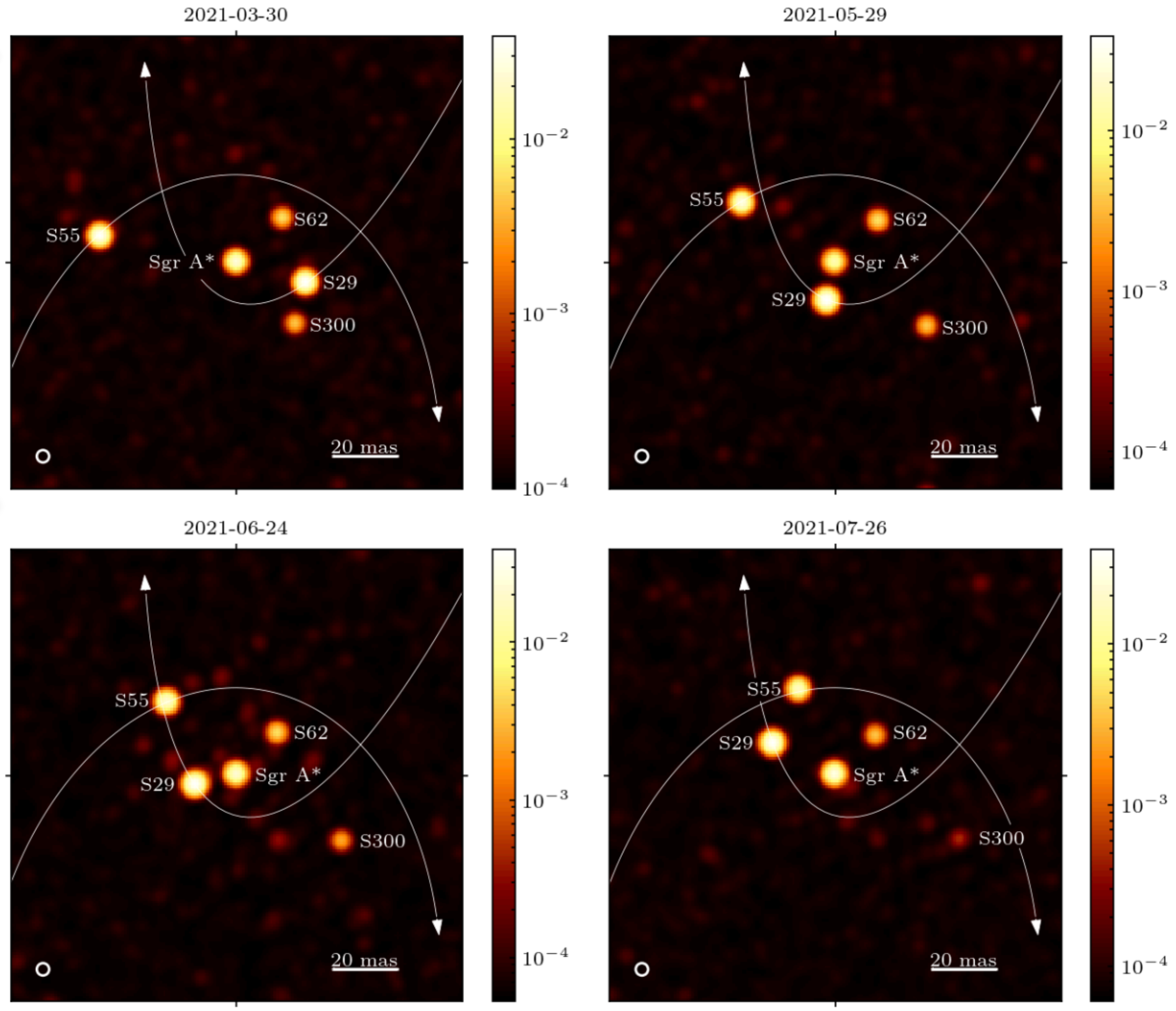
The innermost 0.6 pc





The deepest Image of the GC through GRAVITY





GRAVITY Collaboration et al. 2022

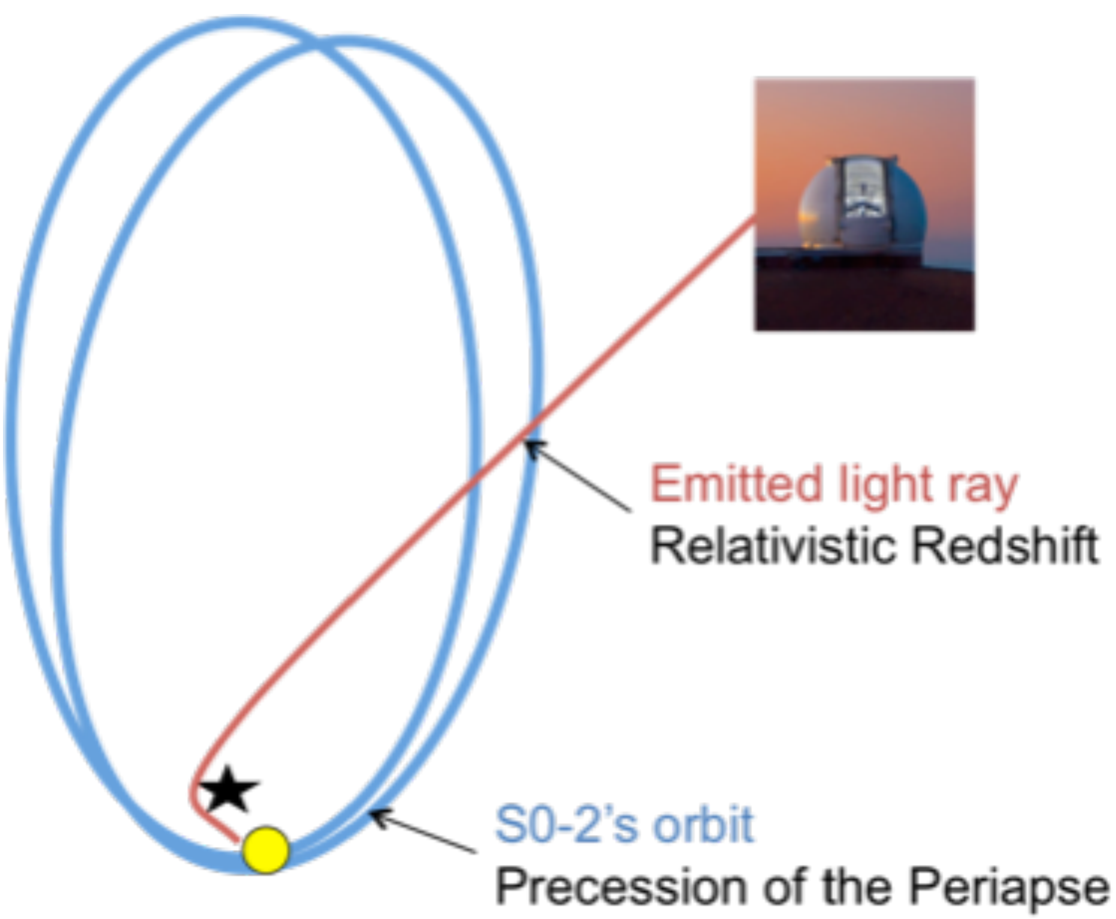
Stellar Orbits

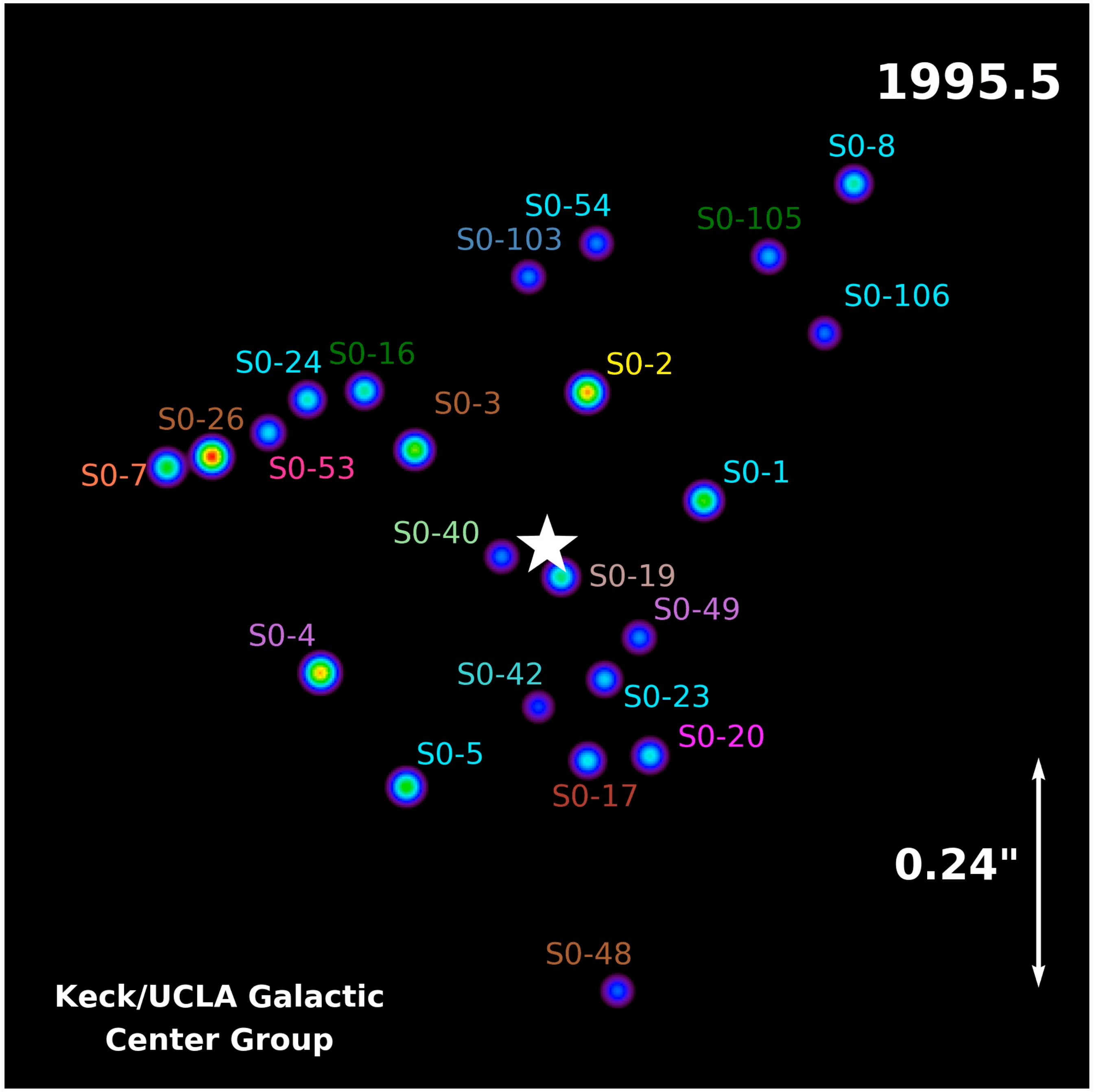
UCLA

Andrea Ghez, Mark Morris, Eric Becklin, Tuan Do, Aurelien Hees, Shoko Sakai, Jessica Lu, Devin Chu…

Galactic center in the NIR: Dynamics of the S- star cluster

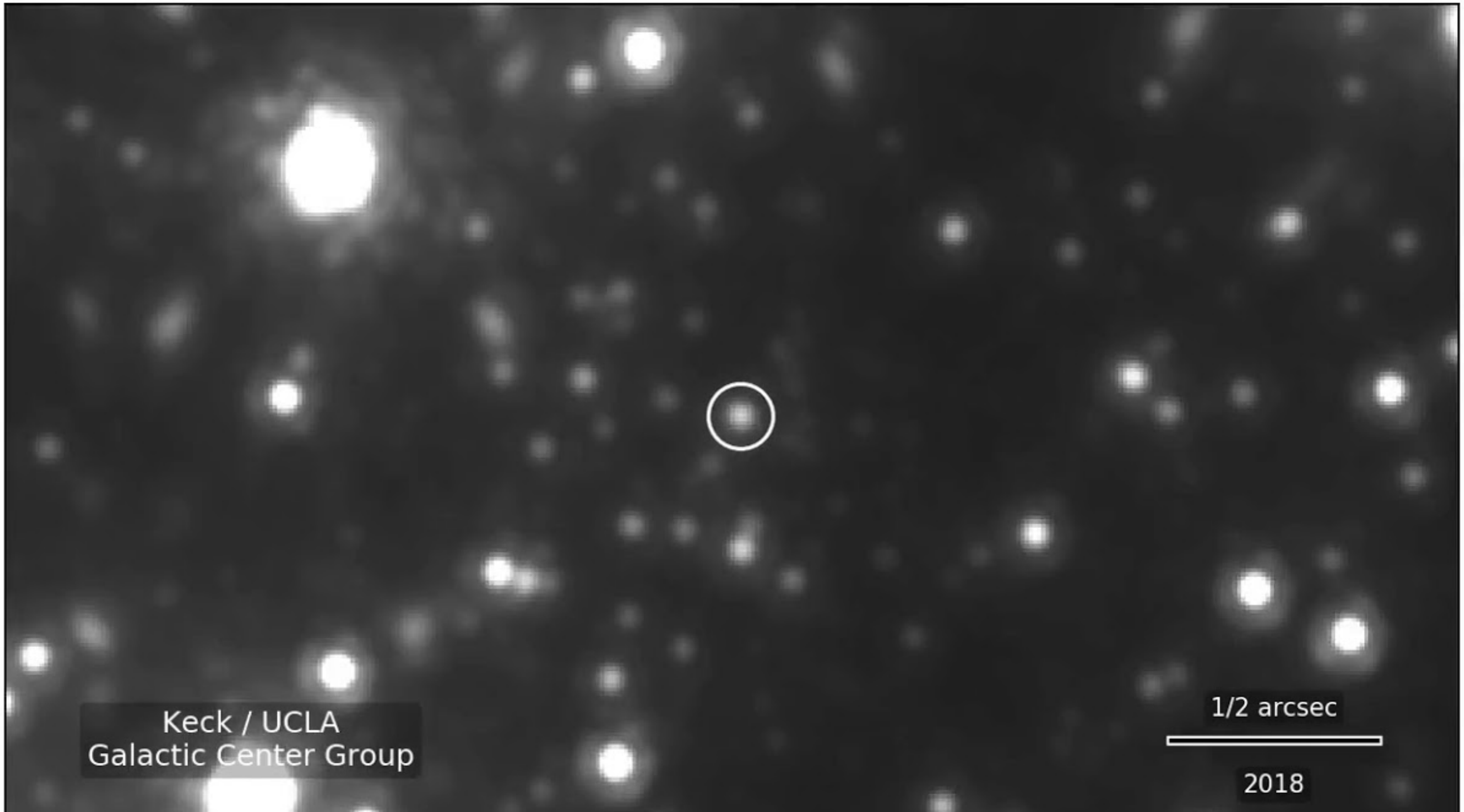
NIRC2 @ Keck2

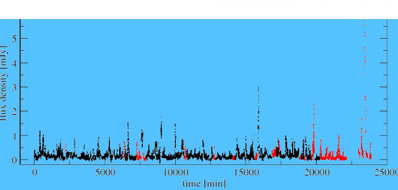


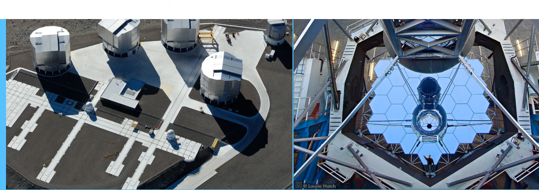


Galactic center in the NIR: Dynamics of the S- star cluster

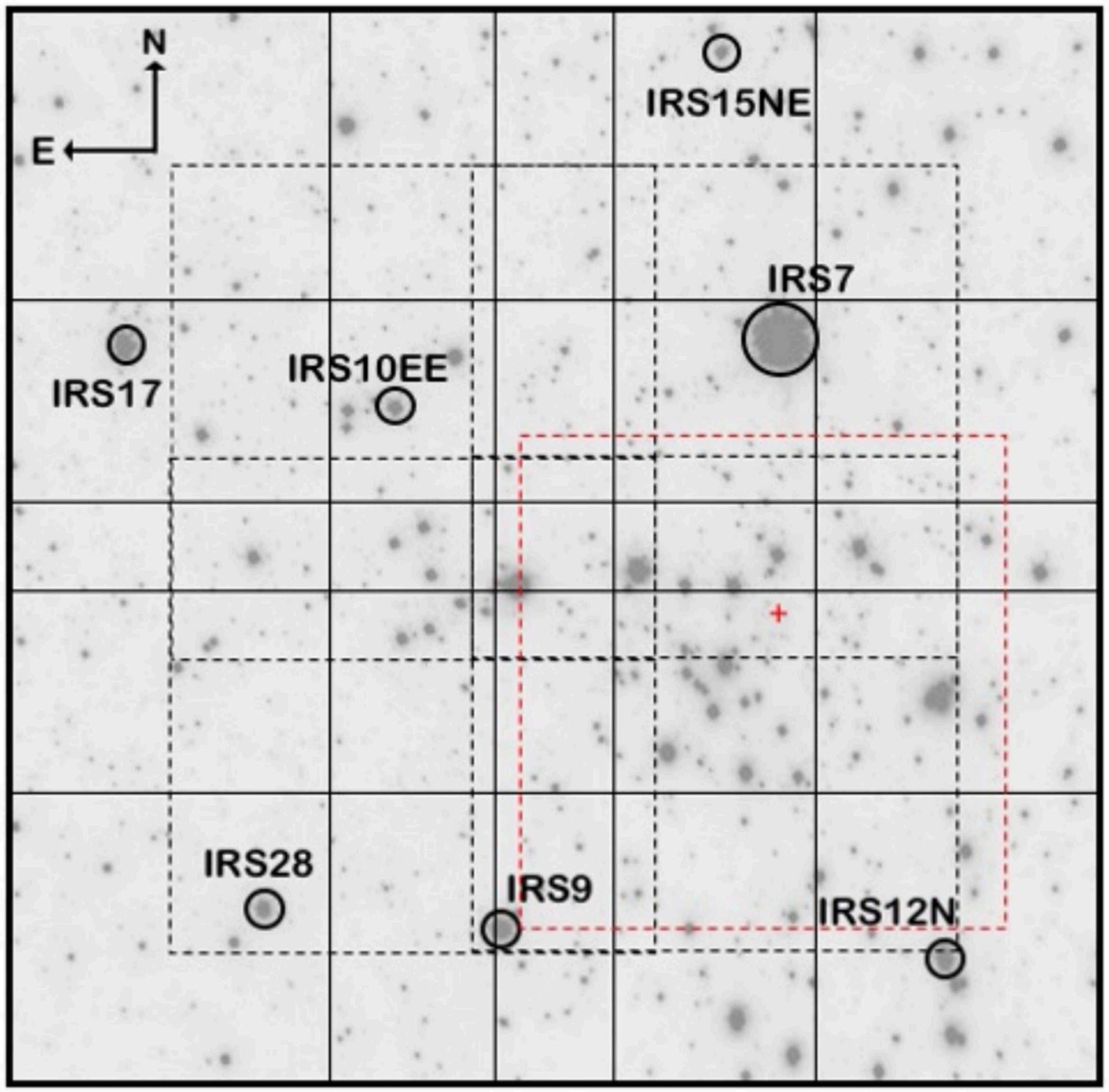
NIRC2 @ Keck2







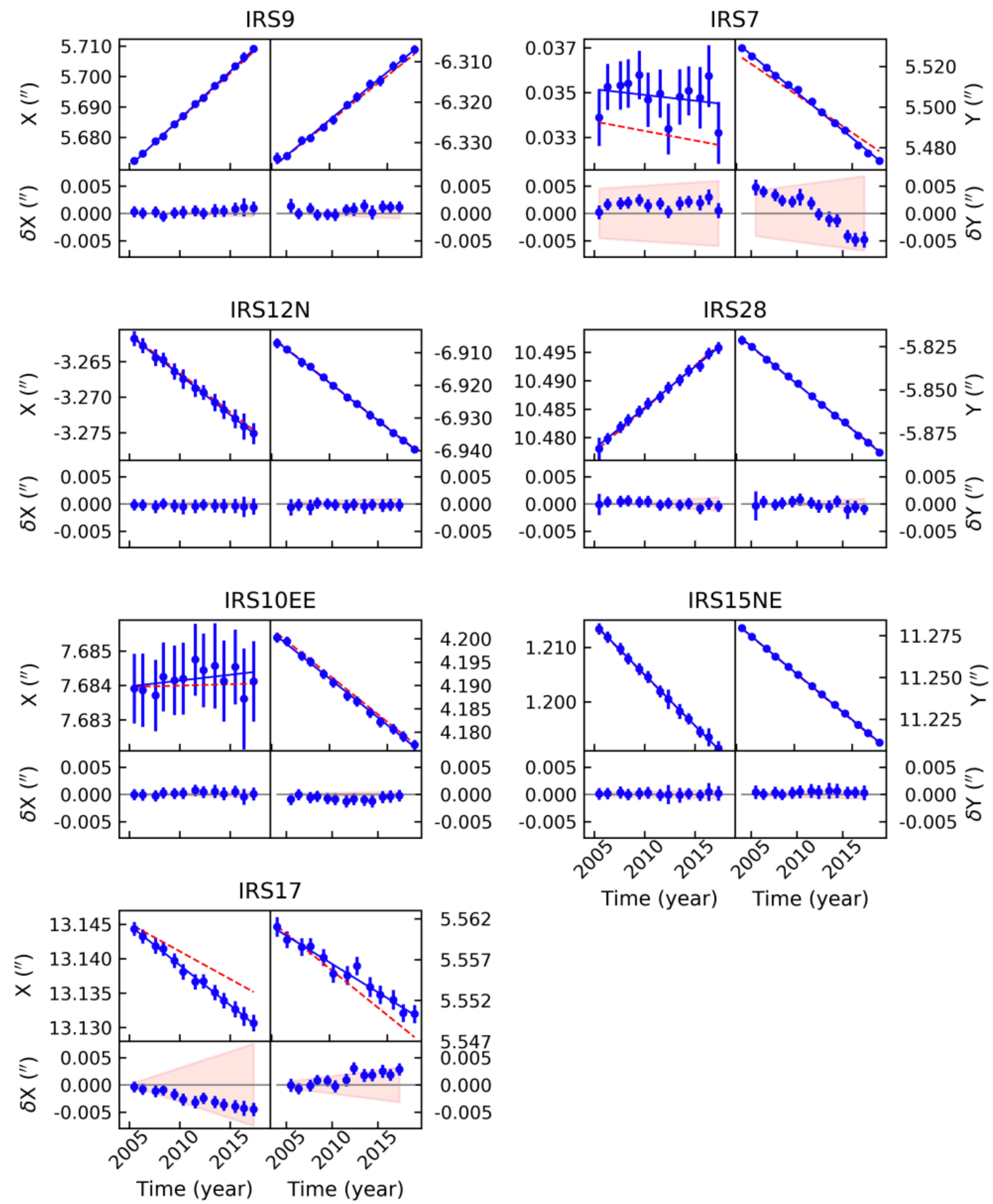
Reference frame



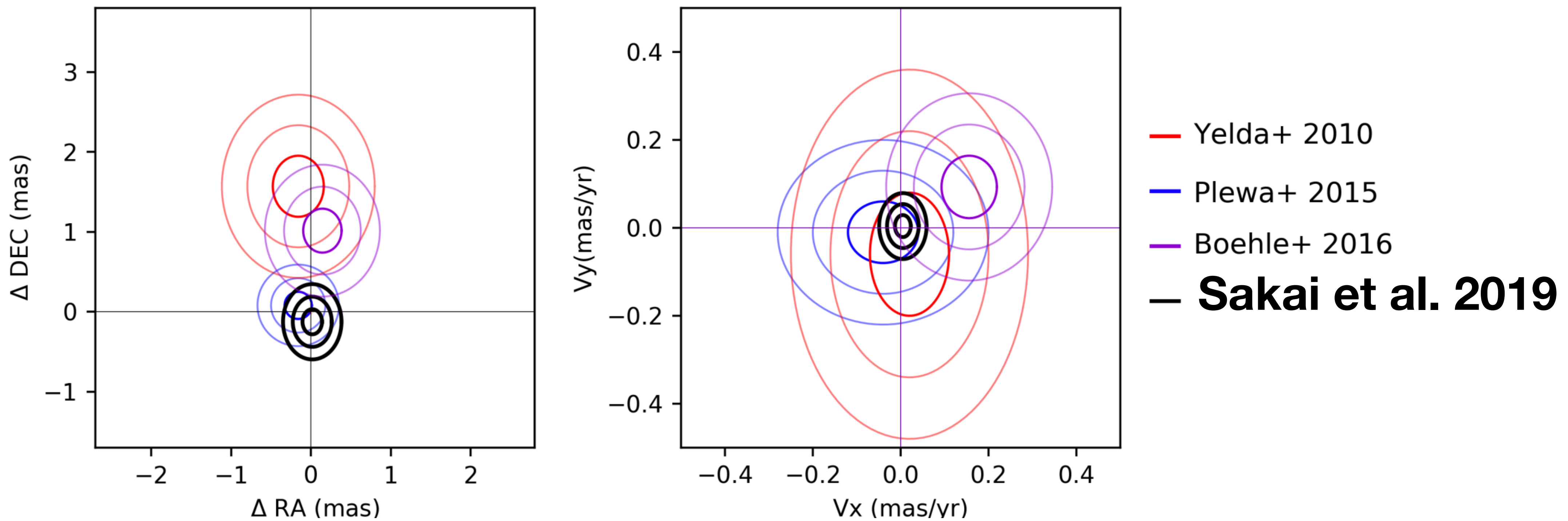
Sakai et al. 2019

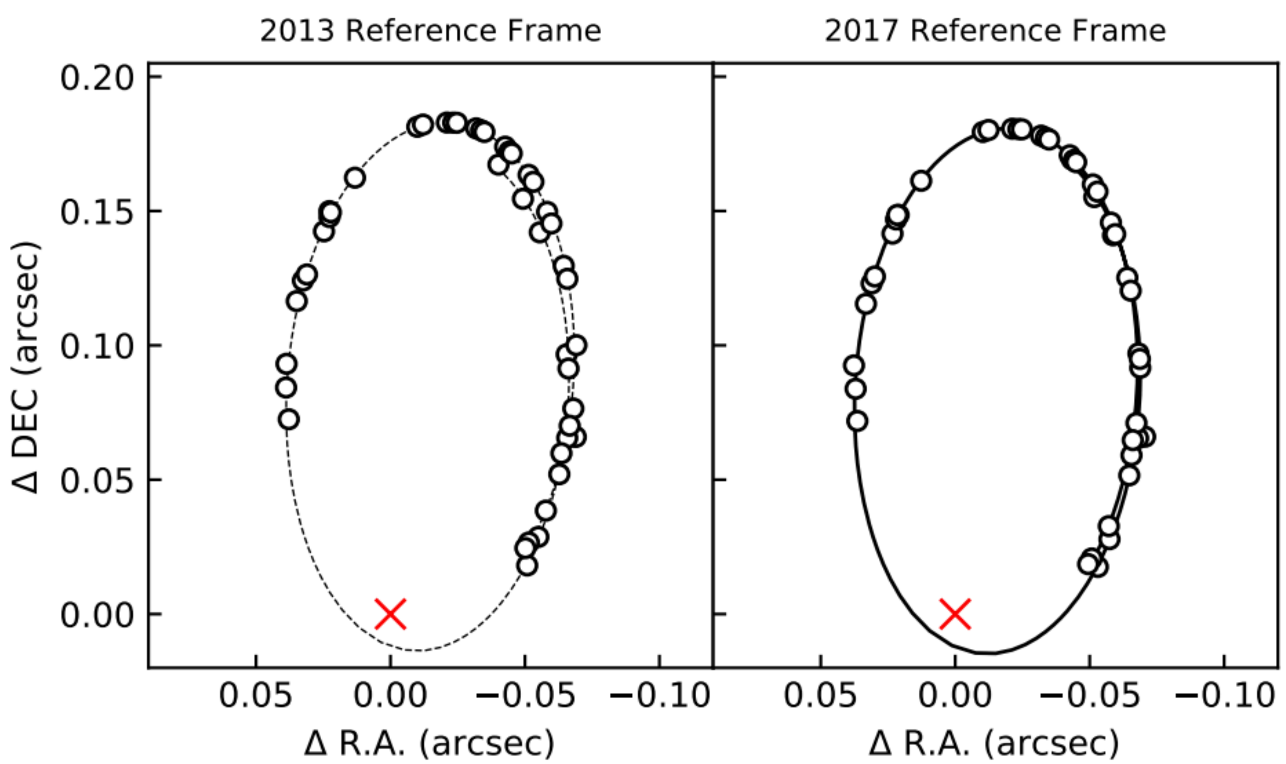
Reid 2018 privat communication

(Reid at al. 2007)



Reference frame

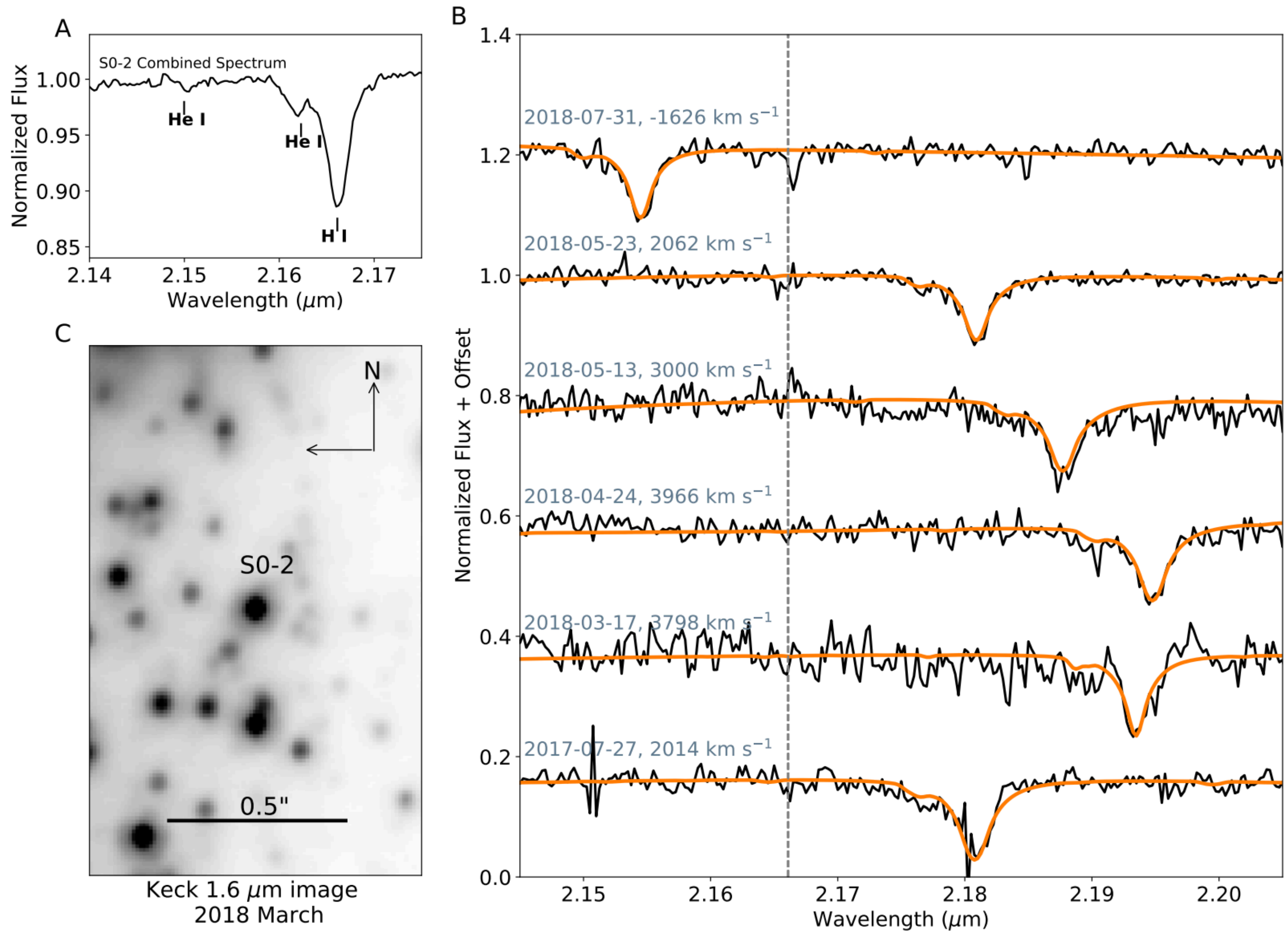




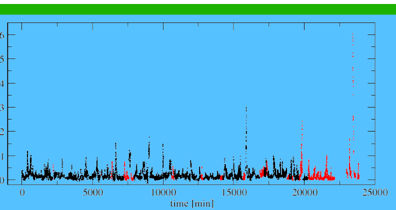
Sakai et al. 2019

Galactic center in the NIR: Dynamics of the S- star cluster

NIRC2 @ Keck2

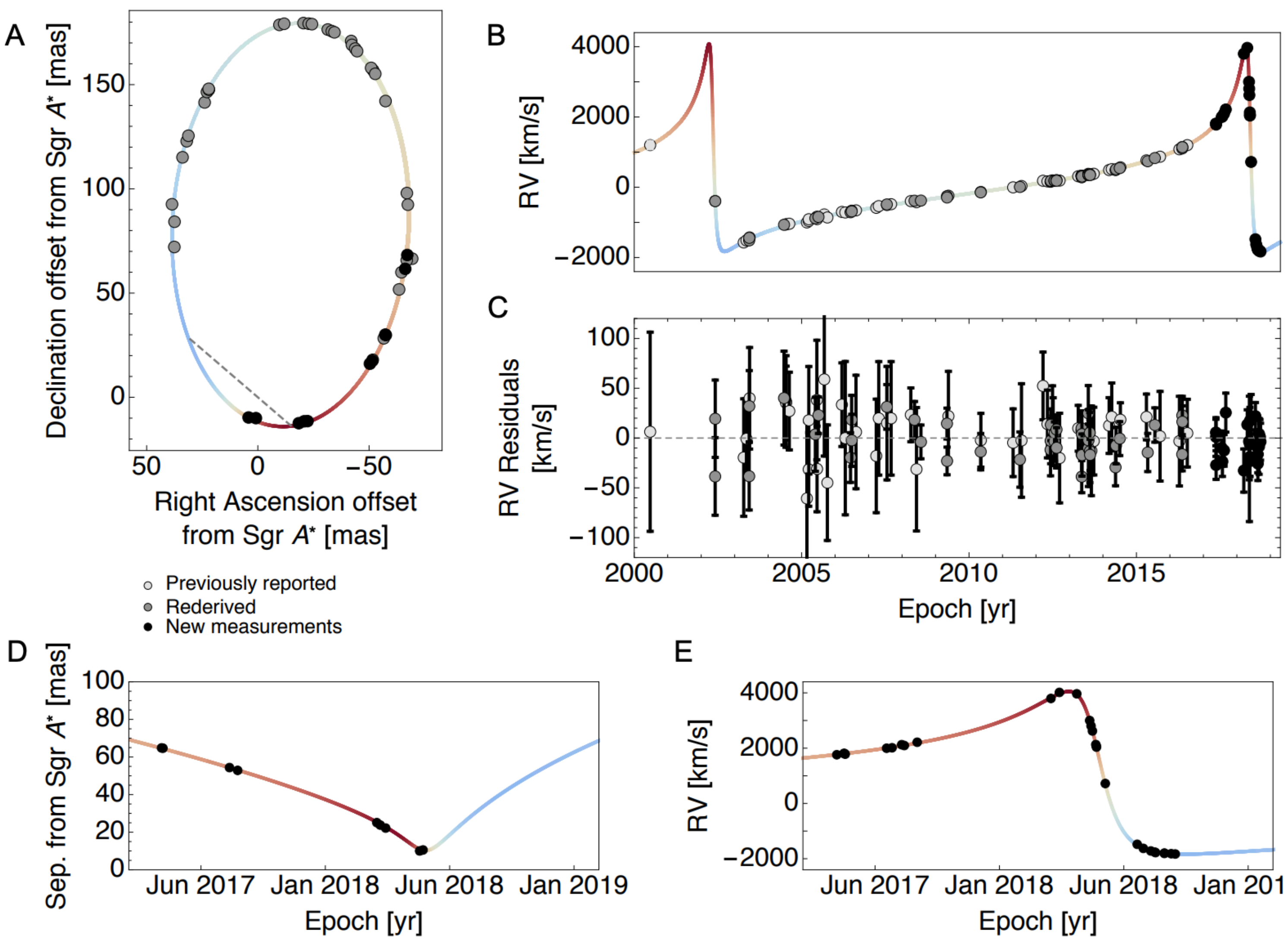


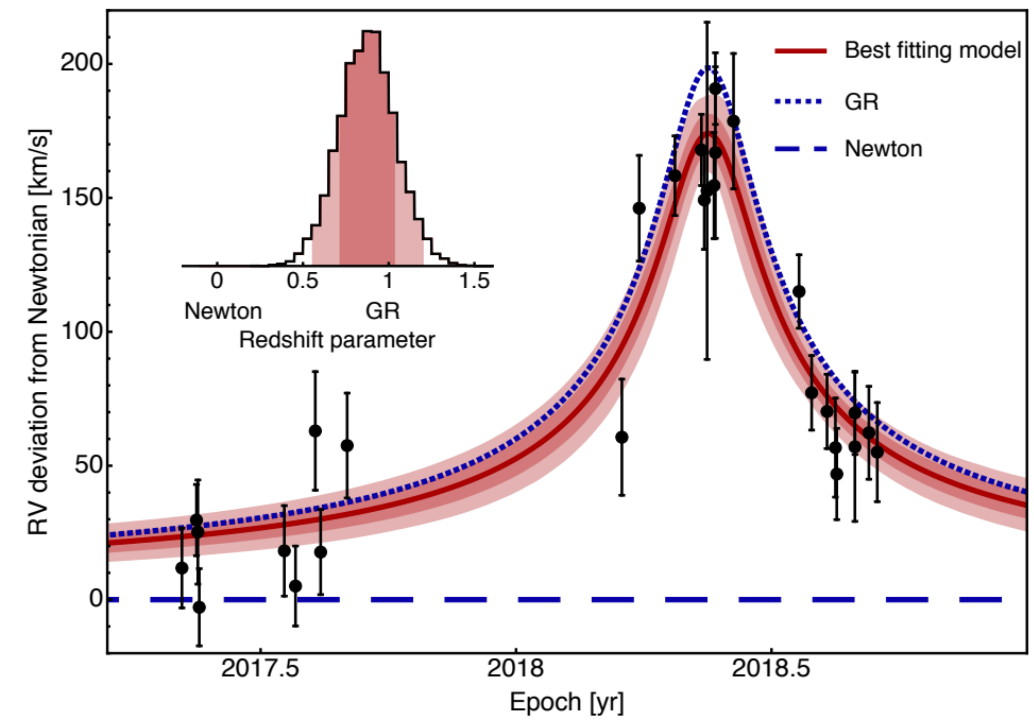
Do et al. 2019



Galactic center in the NIR: Dynamics of the S- star cluster

NIRC2 @ Keck2





$$RV = v_{z_0} + V_{Z,\mathrm{S0-2}} + \Upsilon \left[\frac{V_{\mathrm{S0-2}}^2}{2c} + \frac{GM}{cR_{\mathrm{S0-2}}} \right]$$

Do et al. 2019


South - Thu May 17 04:08:03 2018

BH parameters

KECK:

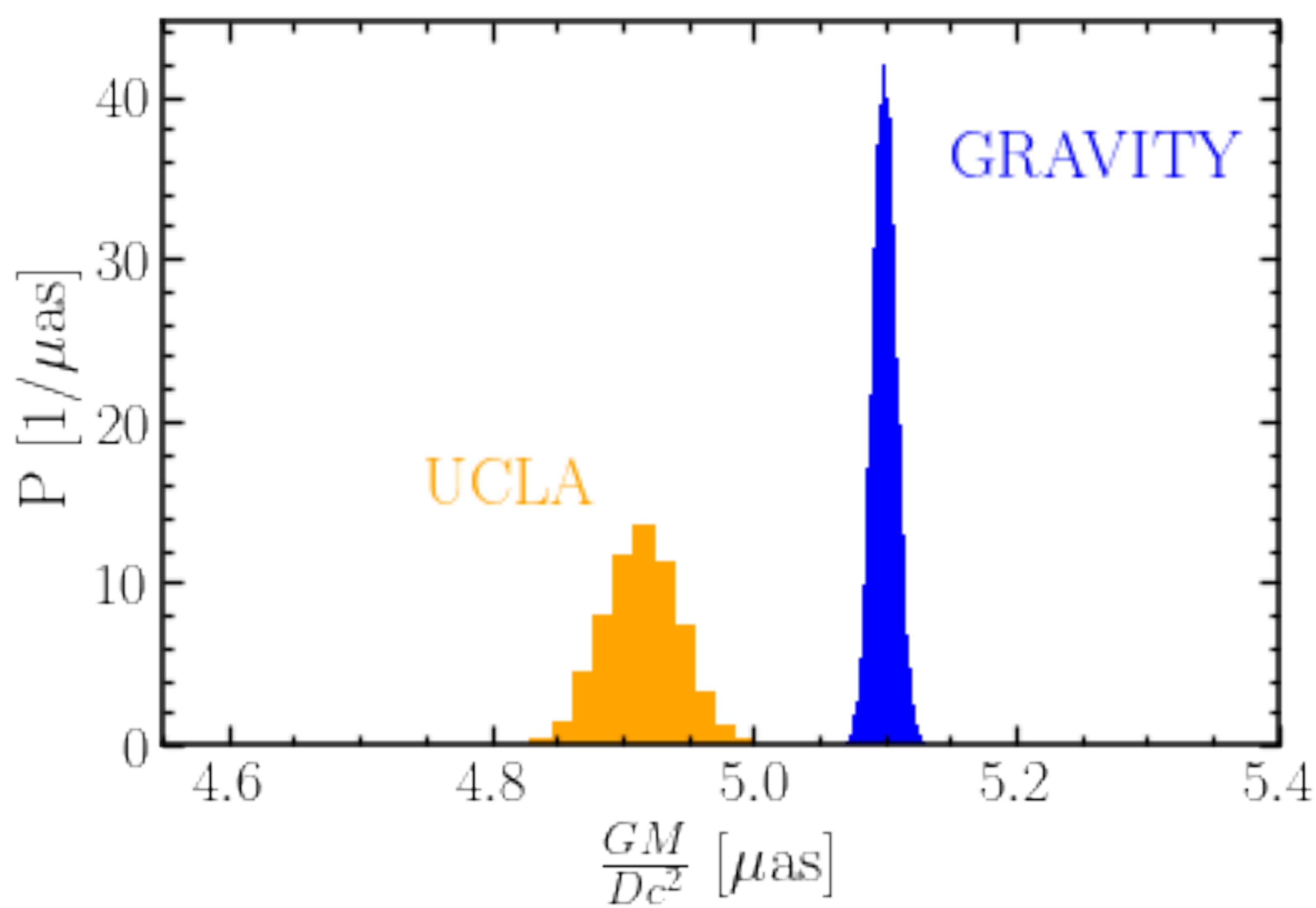
$M = (3.975 \pm 0.058 \pm 0.025) \times 10^6 M_\odot$

$R_0 = (7959 \pm 59 \pm 32)$ pc

GRAVITY:

$M = (4.297 \pm 0.012 \pm 0.040) \times 10^6 M_\odot$

$R_0 = (8277 \pm 9 \pm 33)$ pc



Reid et al. 2009, 2014, 2019:

$R_0 = (8.15 \pm 0.15)$ kpc

See also GRAVITY Collab. et al. 2018, 2019, 2020a, 2021b, 2022
-> Odele Straub's talk

GC Scales

GC distance ~ 8 kpc
1mas ~ 8 AU ~ 1 light hour
R_s ~ 10 μas ~ 0.08 AU
Periapsis distance G2 ~ 200 AU
Periapsis distance G1 ~ 300 AU
Periapsis distance S0-2 ~120 AU ~ 17 light hours

Tidally interacting sources G1 and G2

UCLA

Andrea Ghez, Mark Morris, Breann Sitarski, Eric Becklin, Tuan Do

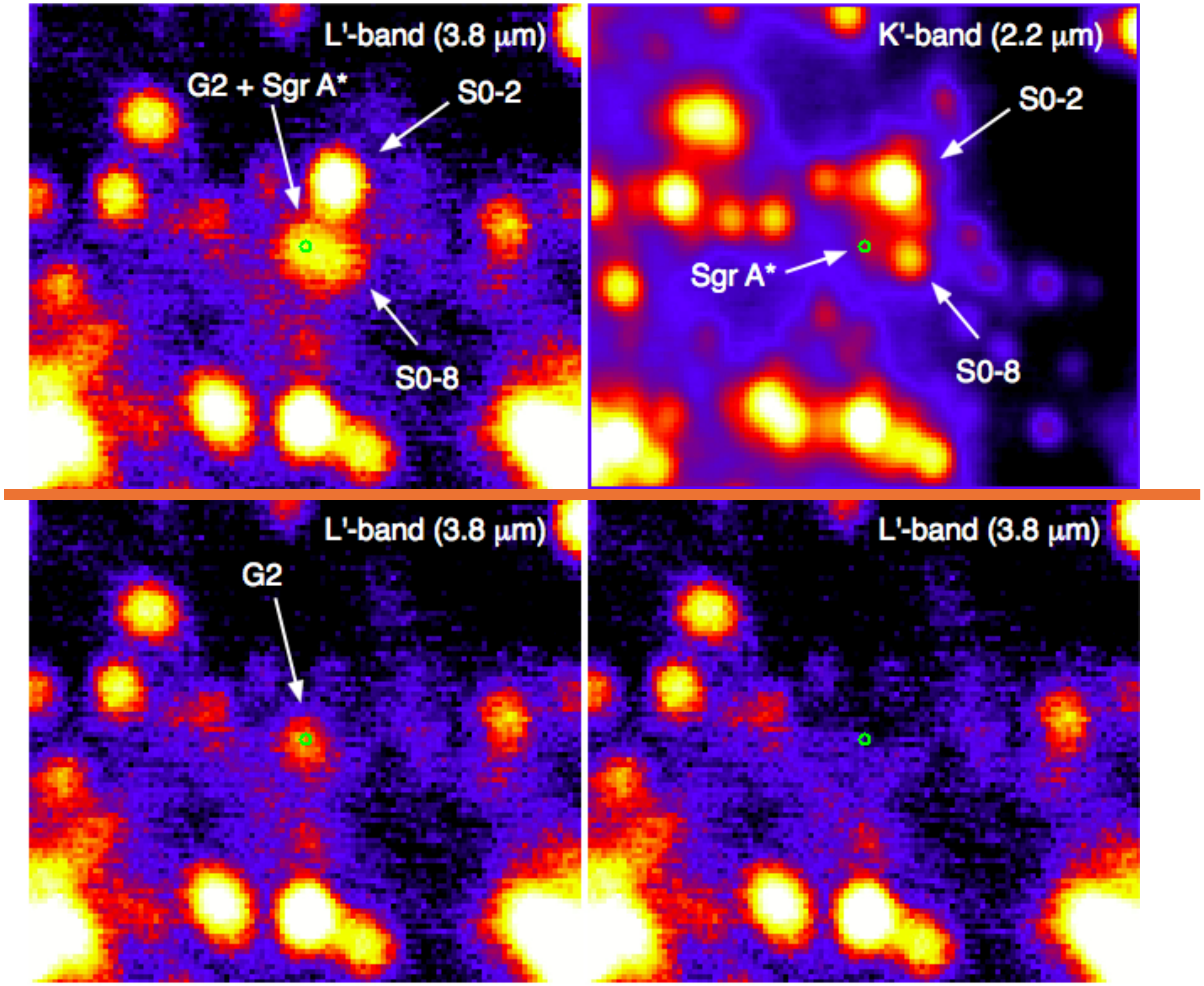
Keck observing campaign 2014 around periapse passage

- March - August
- NIRC2
- interleaving K'- and L'-observations

partly based on ToO
many thanks to

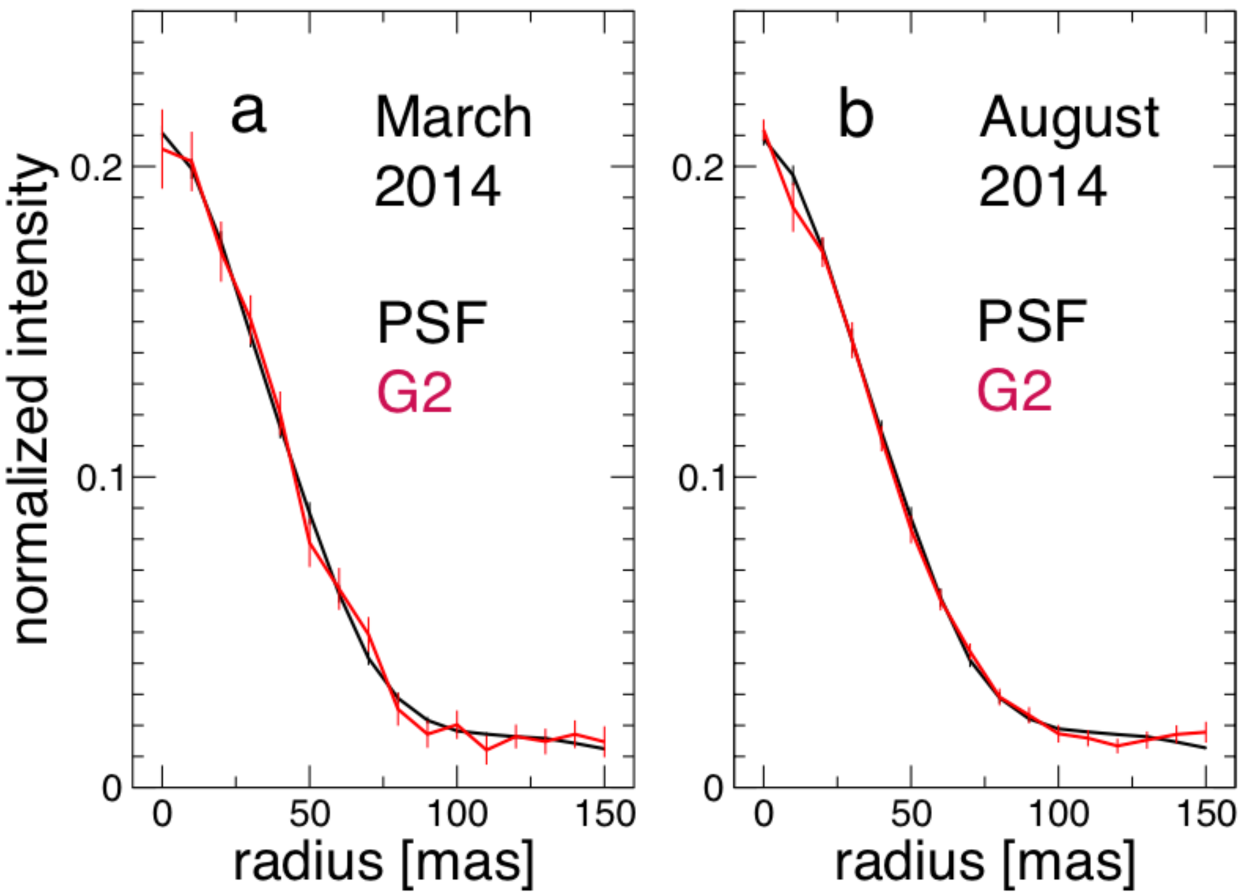
Alan Stockton

Gabriela Canalizo

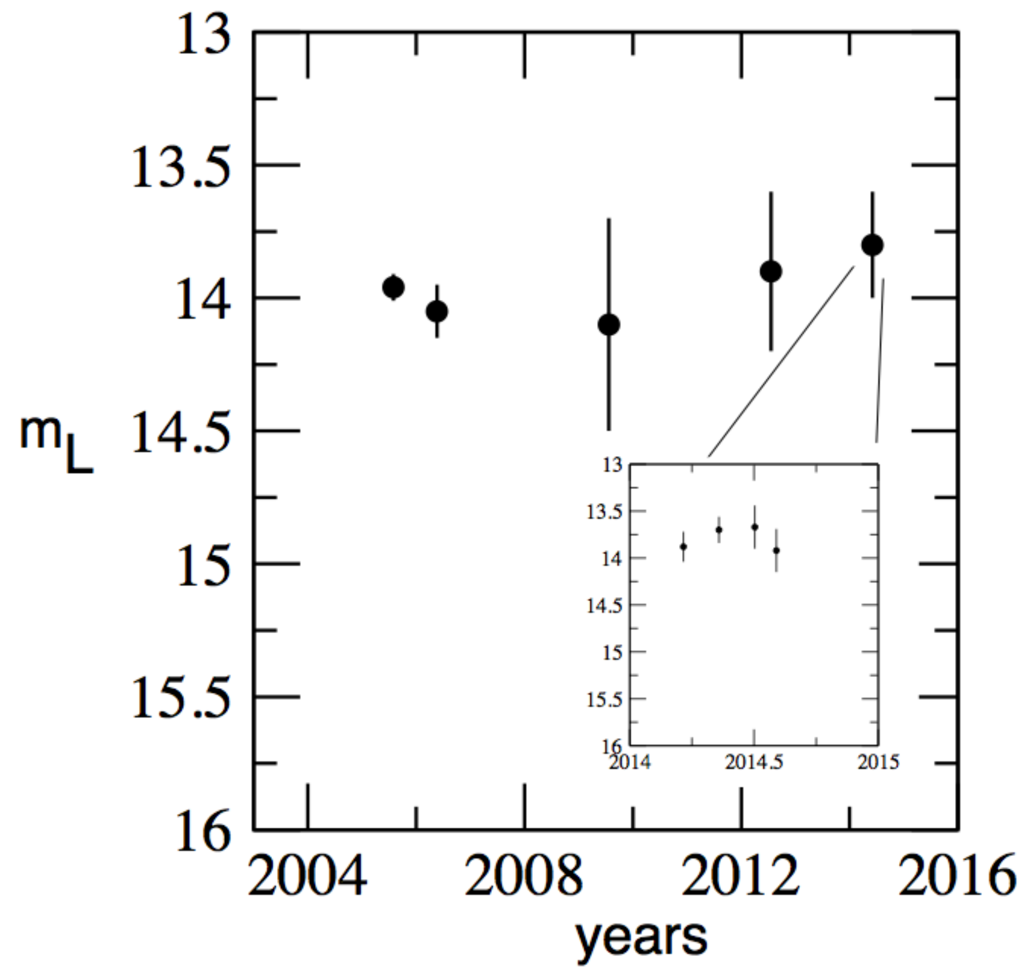


G2 is compact!

despite of a factor of 10 change in distance from the black hole



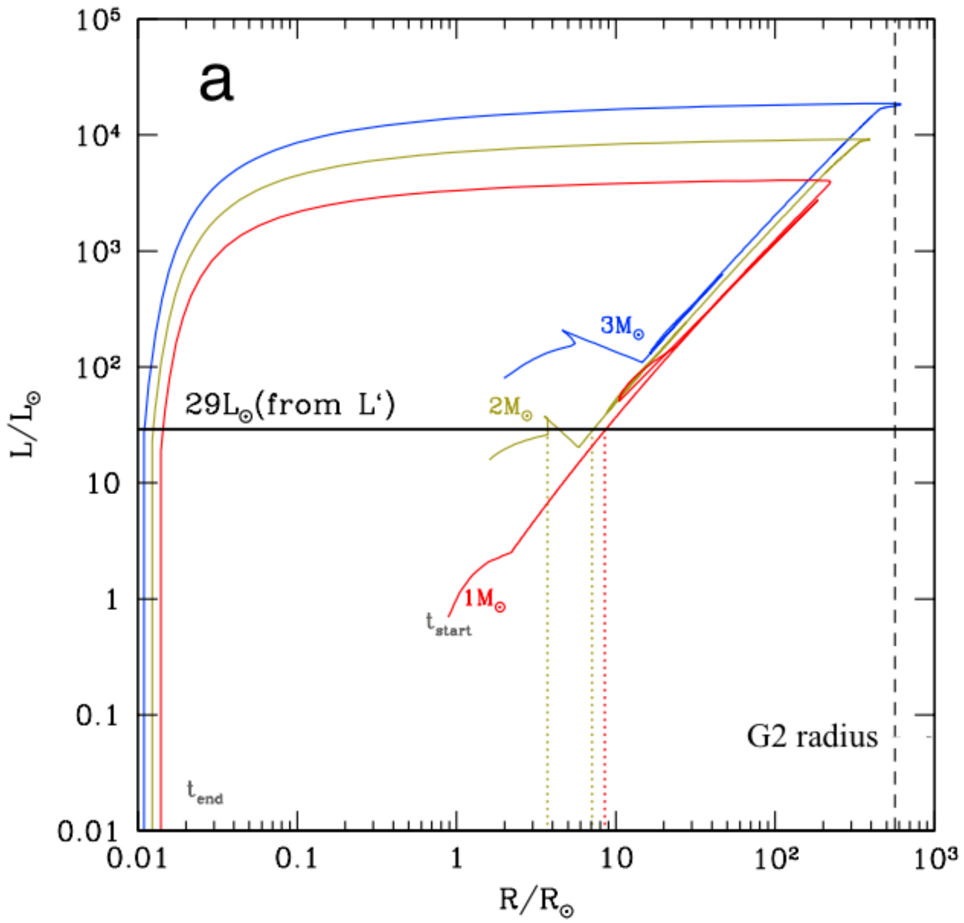
Upper size limit:
260 AU

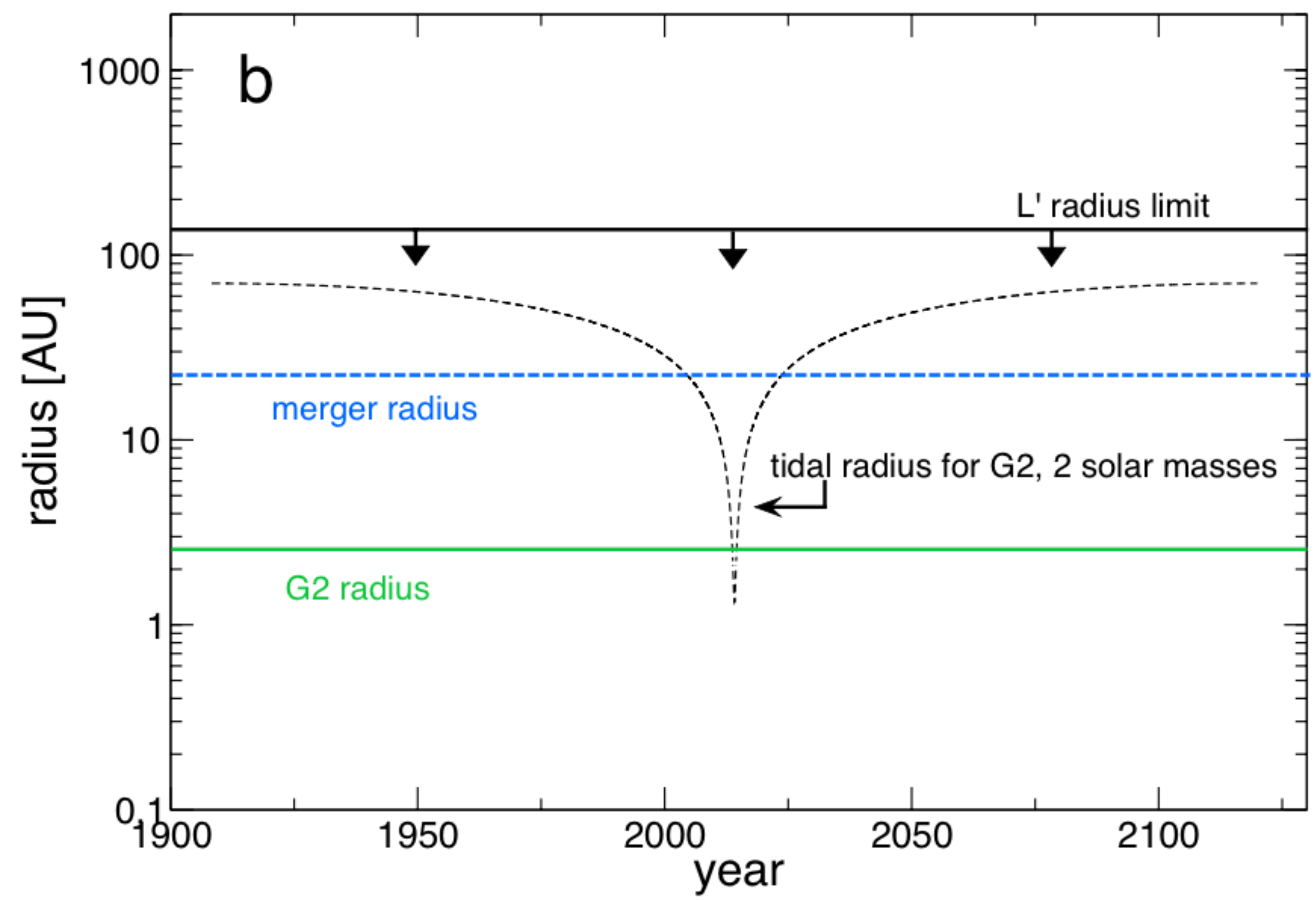


$m_L = 13.8 \pm 0.2$

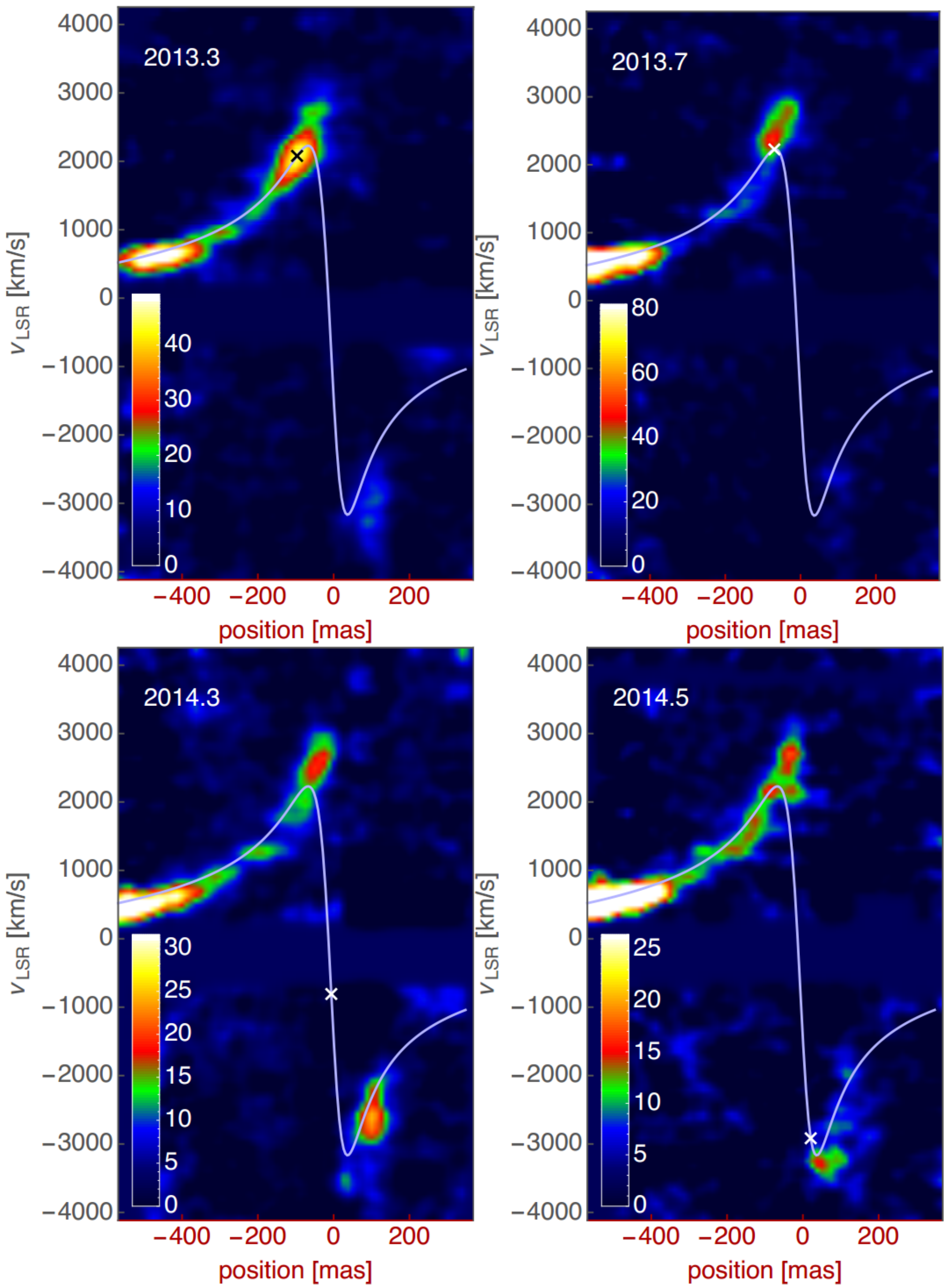
G2 is likely a star!

optically thick black body: L'-flux corresponds to a radius of 2 AU and 29 solar luminosities
temperature: ~560K (M,L',K')



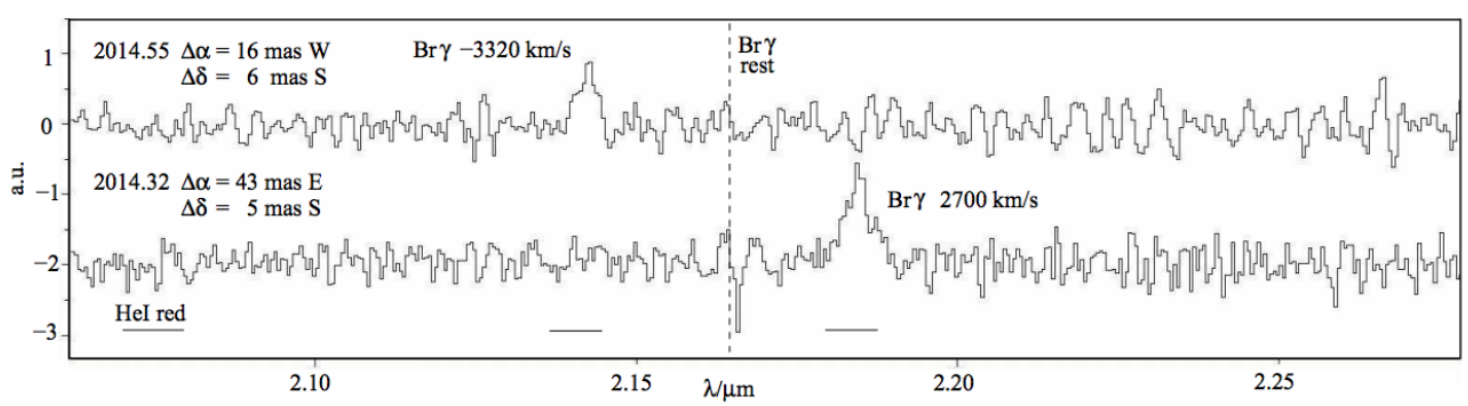


G2 during periapse in Br-gamma

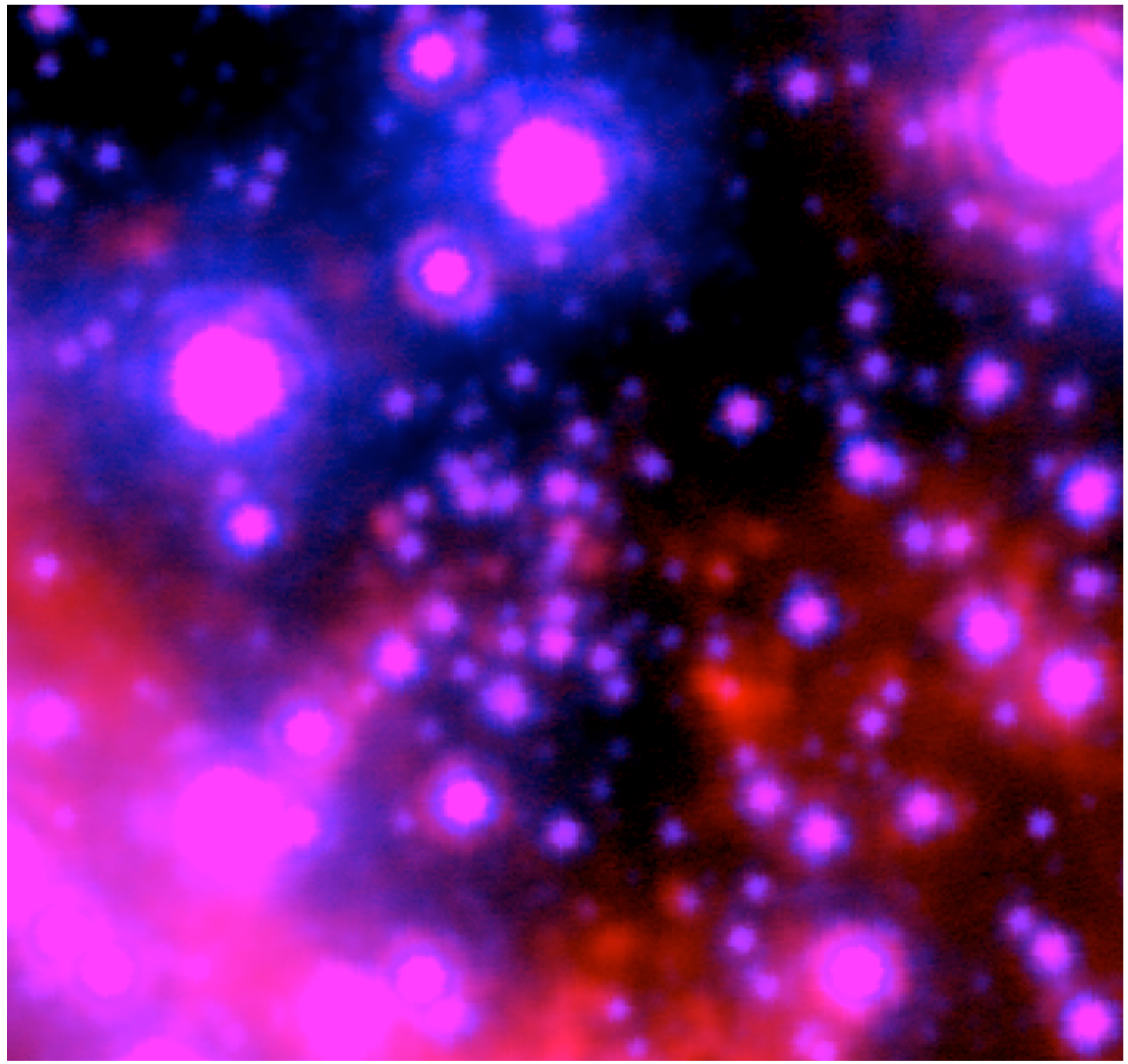


Pfuhl et al. 2014

Valencia-S. et al. 2014

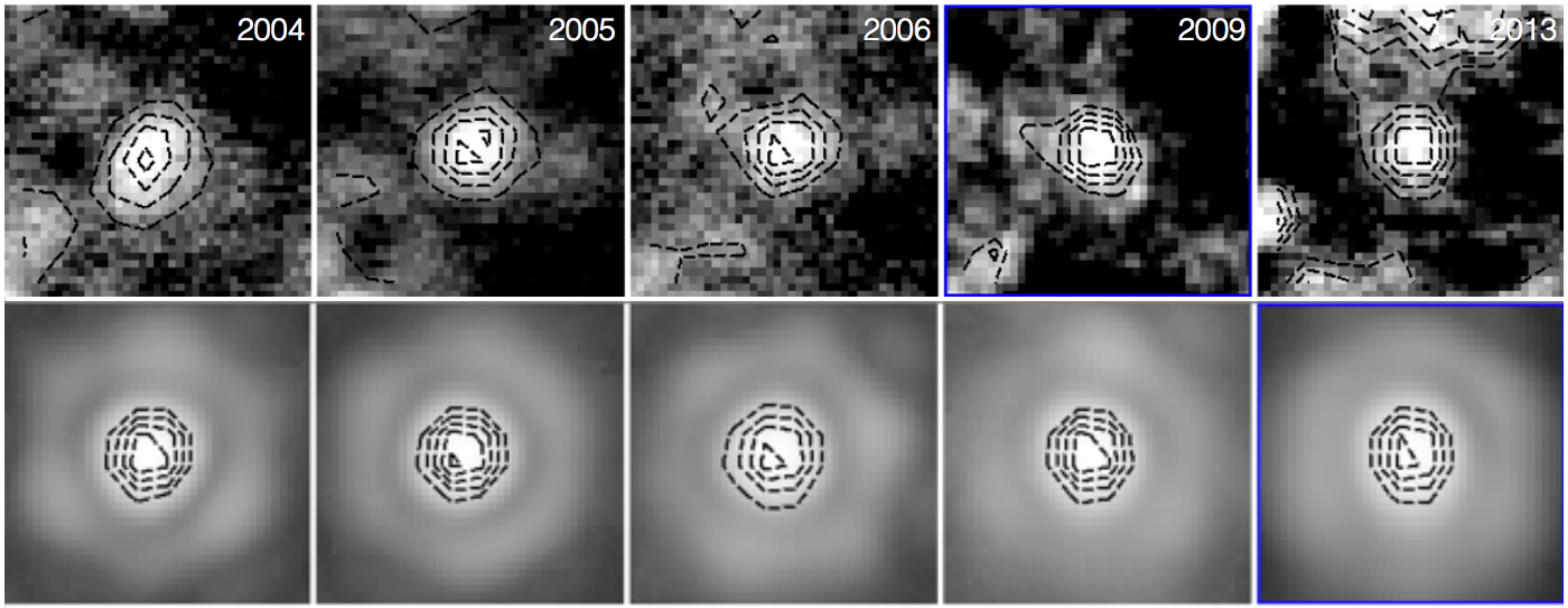


G2 is not alone!



G1: Second example of a source tidally interacting with a SMBH

G1 becomes compact



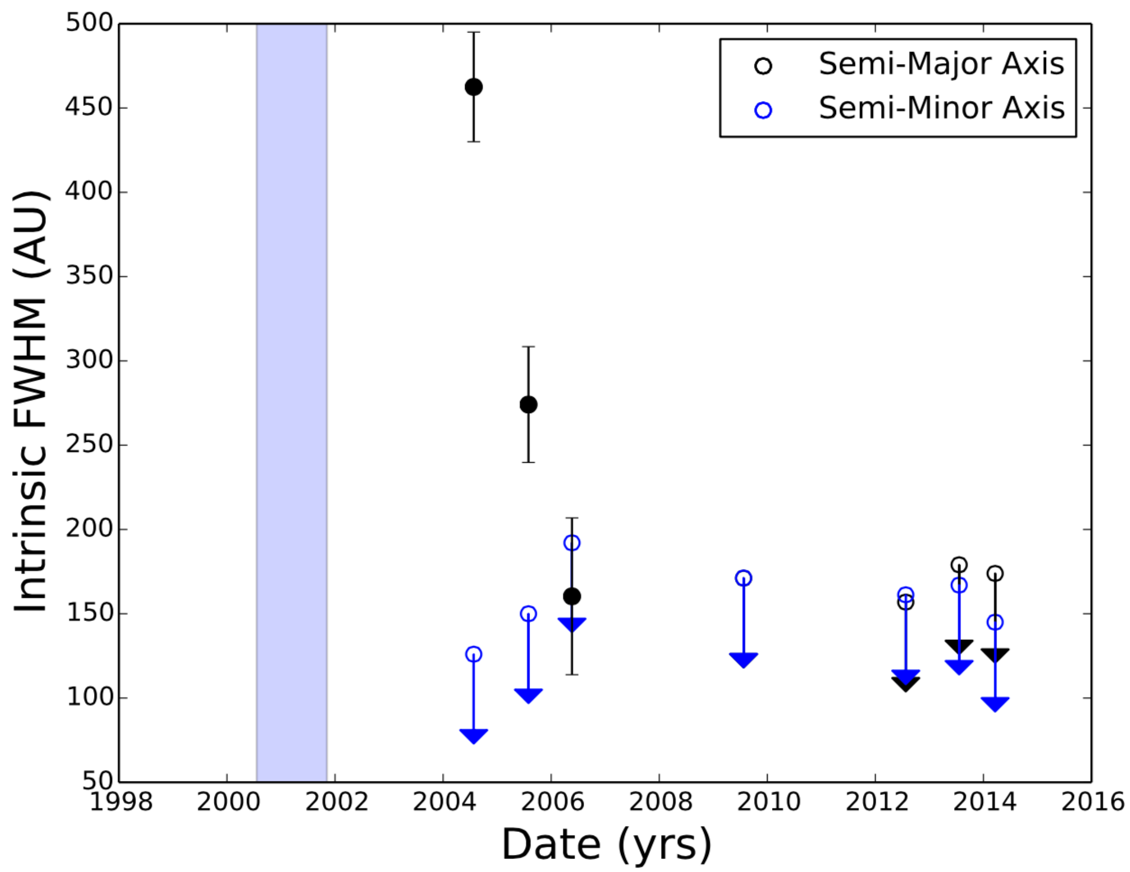
G1

PSF

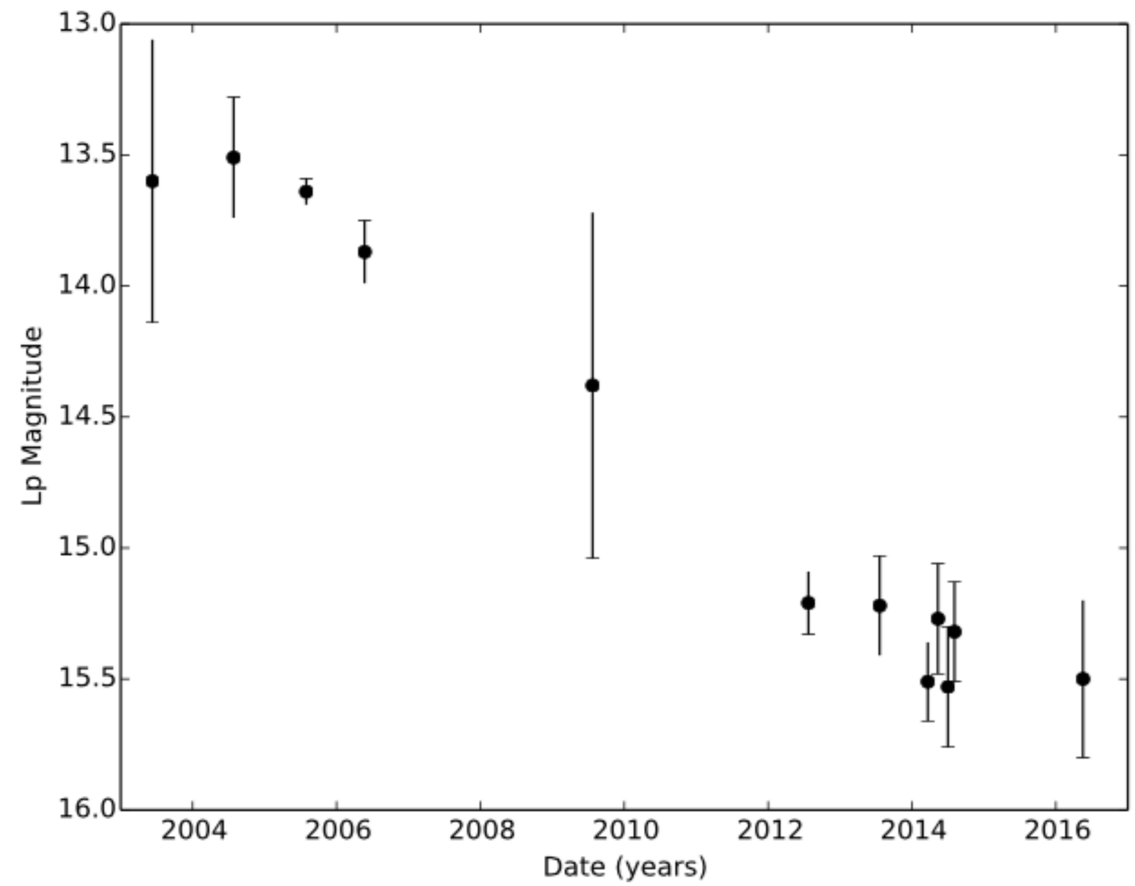
Witzel et. al 2017

G1: Second example of a source tidally interacting with a SMBH

Size



Photometry



Witzel et. al 2017

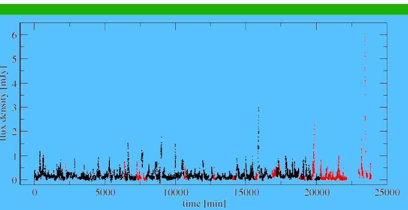
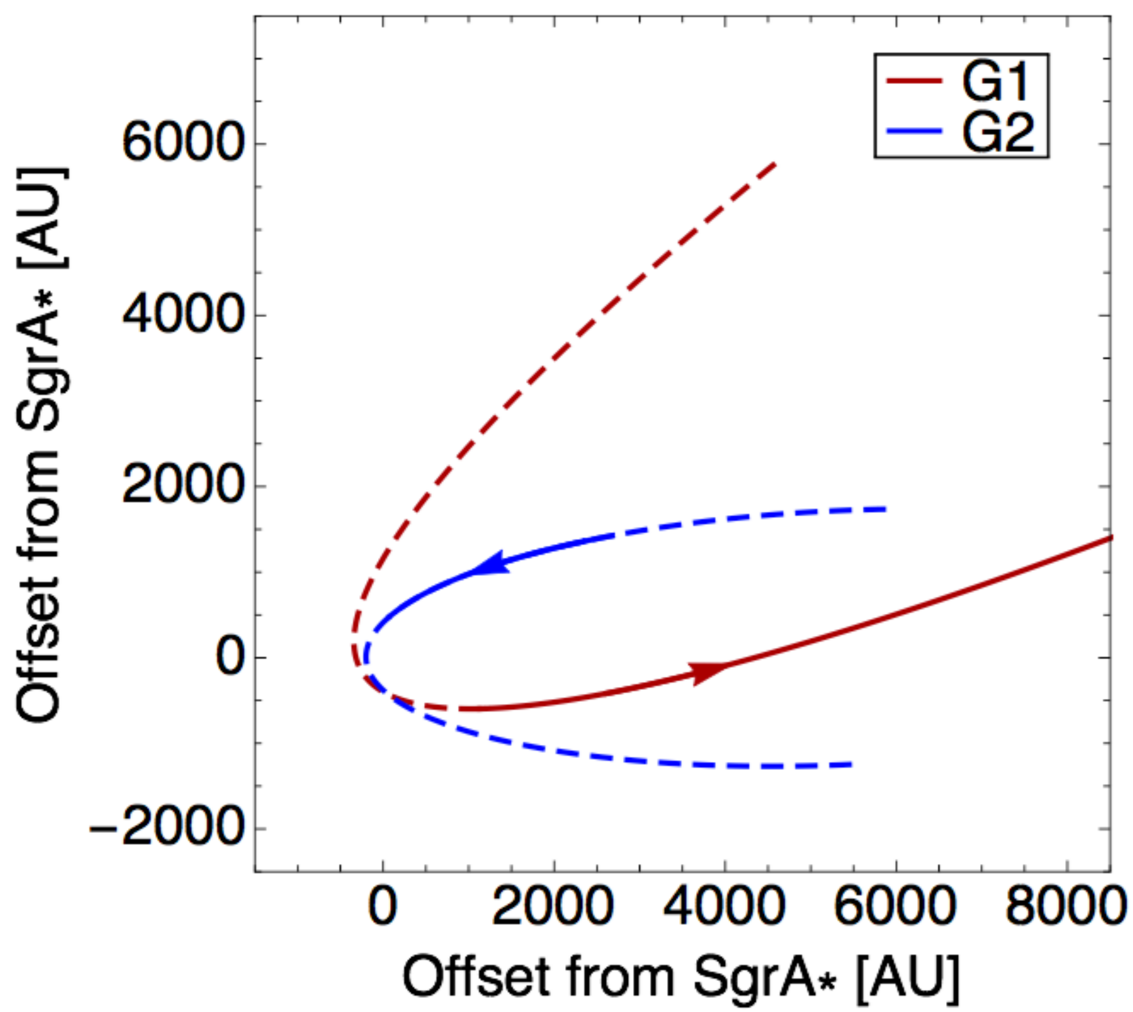


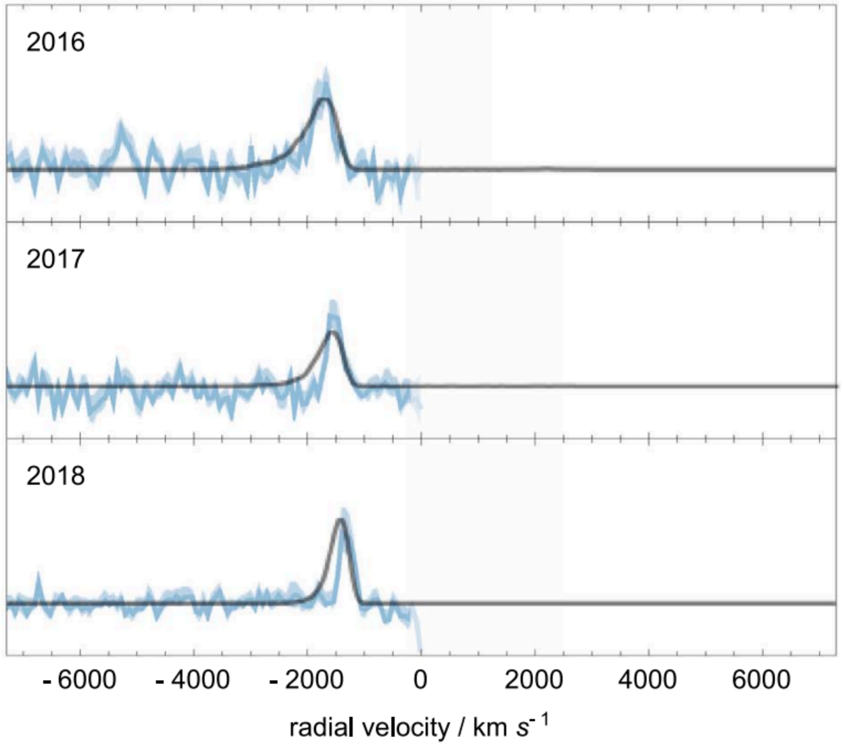
TABLE 5
ORBITAL PARAMETERS FOR G1 AND G2

Parameter	Best Fit, G1	Peak, G1[b]	Best Fit, G2[c]	Peak, G2[c]	G1 Fit Pfuhl et al. (2015)
Time of closest approach (T_0, years)	2001.0	$2001.3^{+0.4}_{-0.2}$	2014.1	$2014.2^{+0.03}_{-0.05}$	2001.6±0.1
Eccentricity (e)	0.981	$0.992^{+0.002}_{-0.01}$	0.962	$0.964^{+0.036}_{-0.073}$	0.860±0.050
Periapse Distance (A_{min}, AU)	277	298^{+32}_{-24}	193	201 ± 13	417 ± 239
Argument of periapse (ω, degrees)	118	117±3	95	96±2	109±8
Inclination (i, degrees)	109	109±1	112	113±2	108±2
Position angle of the ascending node (Ω, degrees)	89	88^{+5}_{-4}	83	82±2	69±5

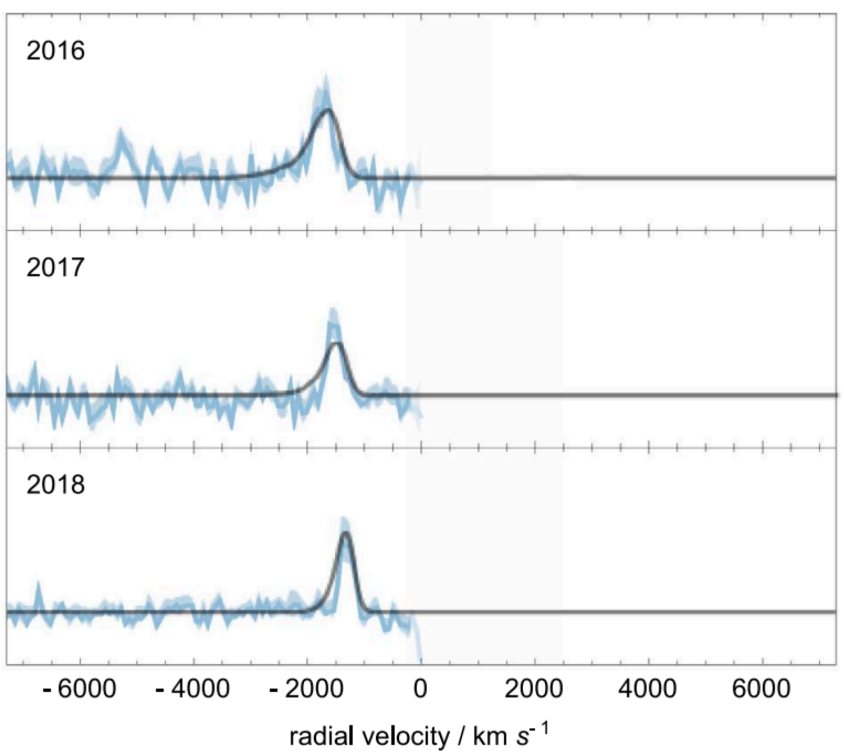
[a] The parameters of Sgr A*are extracted as described above.
[b] The errors reported here are the 1σ errors taken from the marginalized one-dimensional distributions for the respective parameters.
[c] G2 parameters are from performing an orbital fit on our available astrometric and spectroscopic points (those outlined in Meyer et al. 2013) in the same fashion described in Section 3.3.
The clockwise disk parameters are i=130±15 deg and Ω=96±15 deg, where 15 deg reflects the half-width at half-maximum from the peak density of the clockwise disk as reported in Yelda et al. 2014.



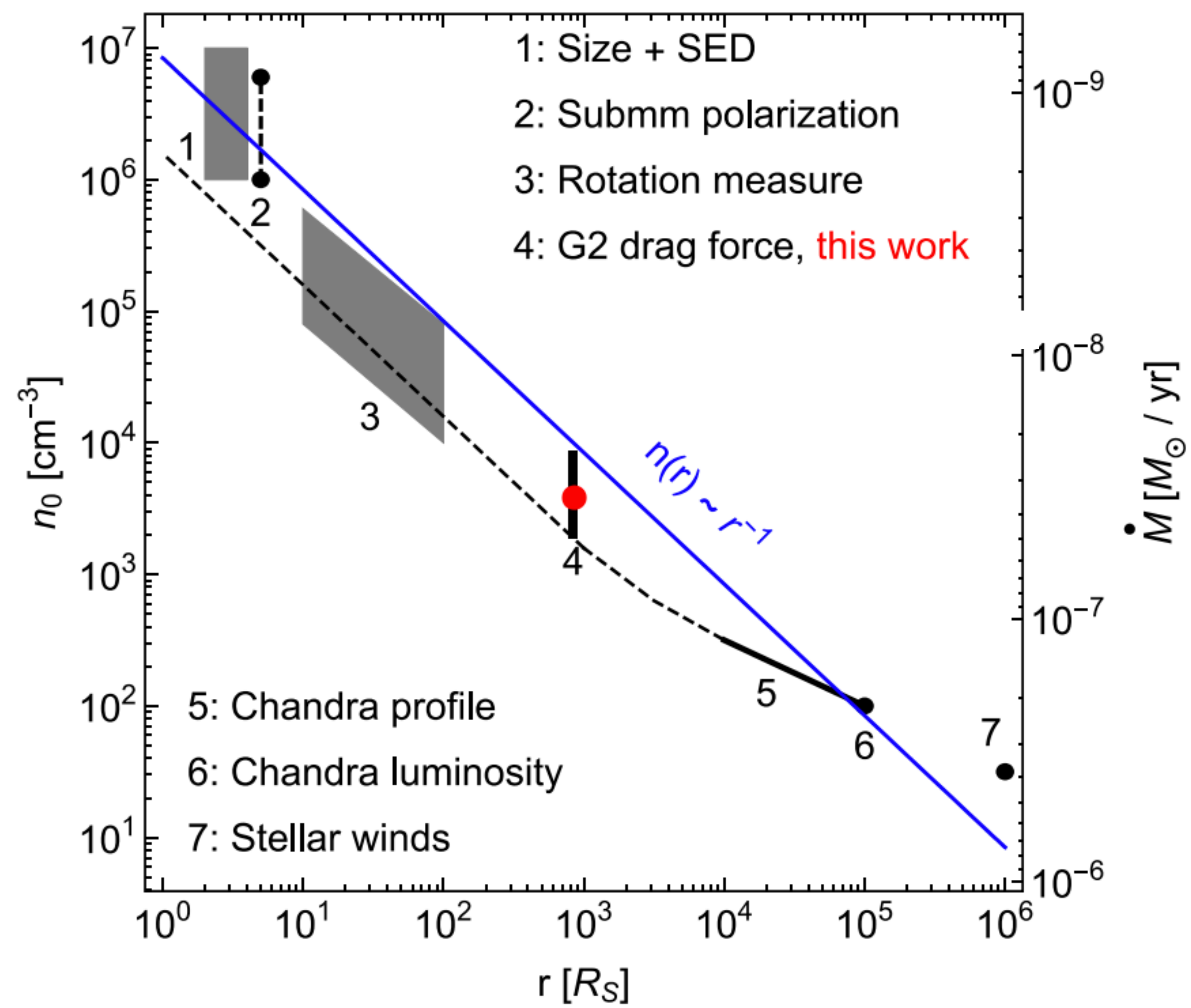
Kepler Fit



Drag Force Fit

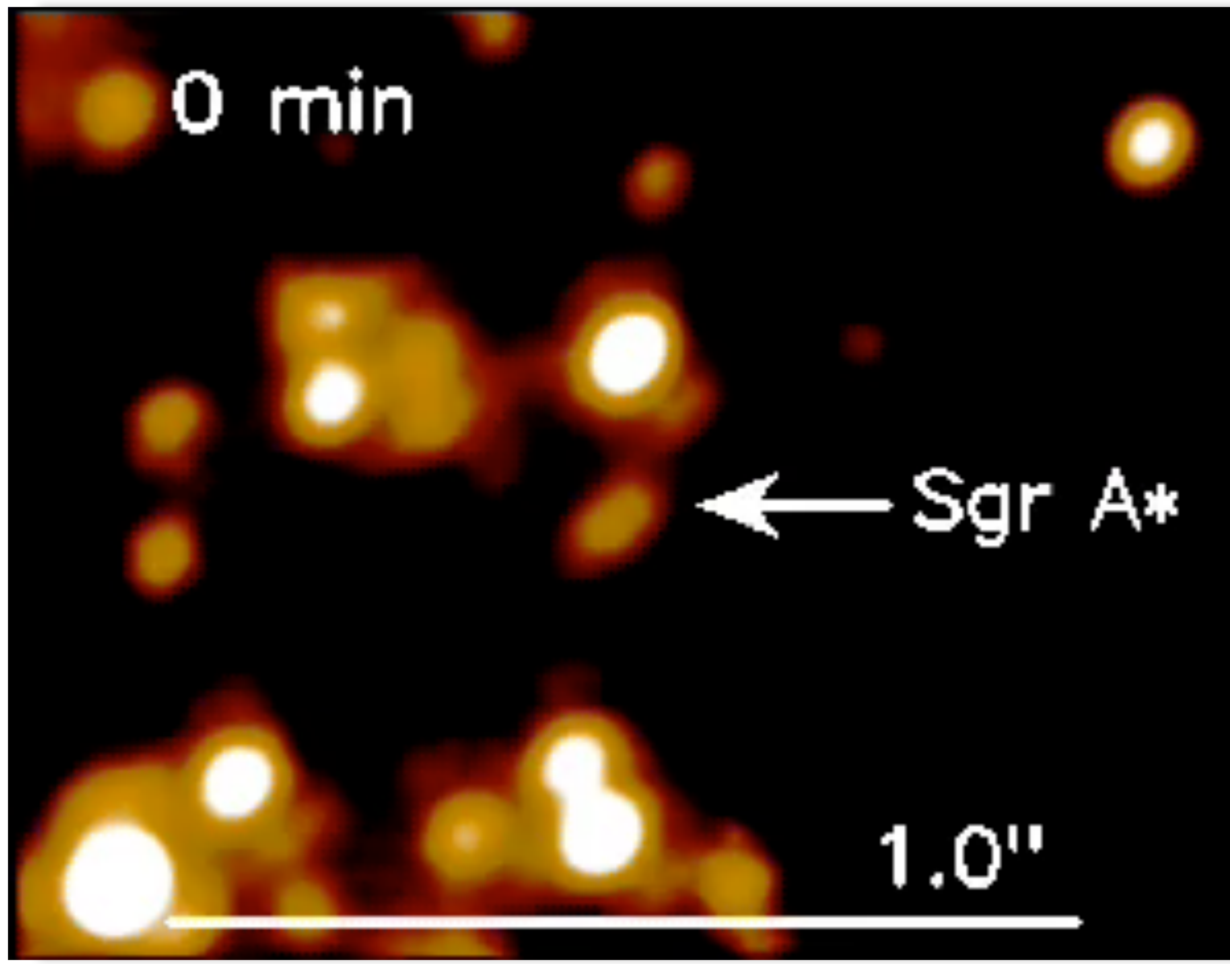


Last chapter so far: Gillessen et al. 2019



Court & Madigan 2016, Madigan et al. 2017

Sagittarius A*

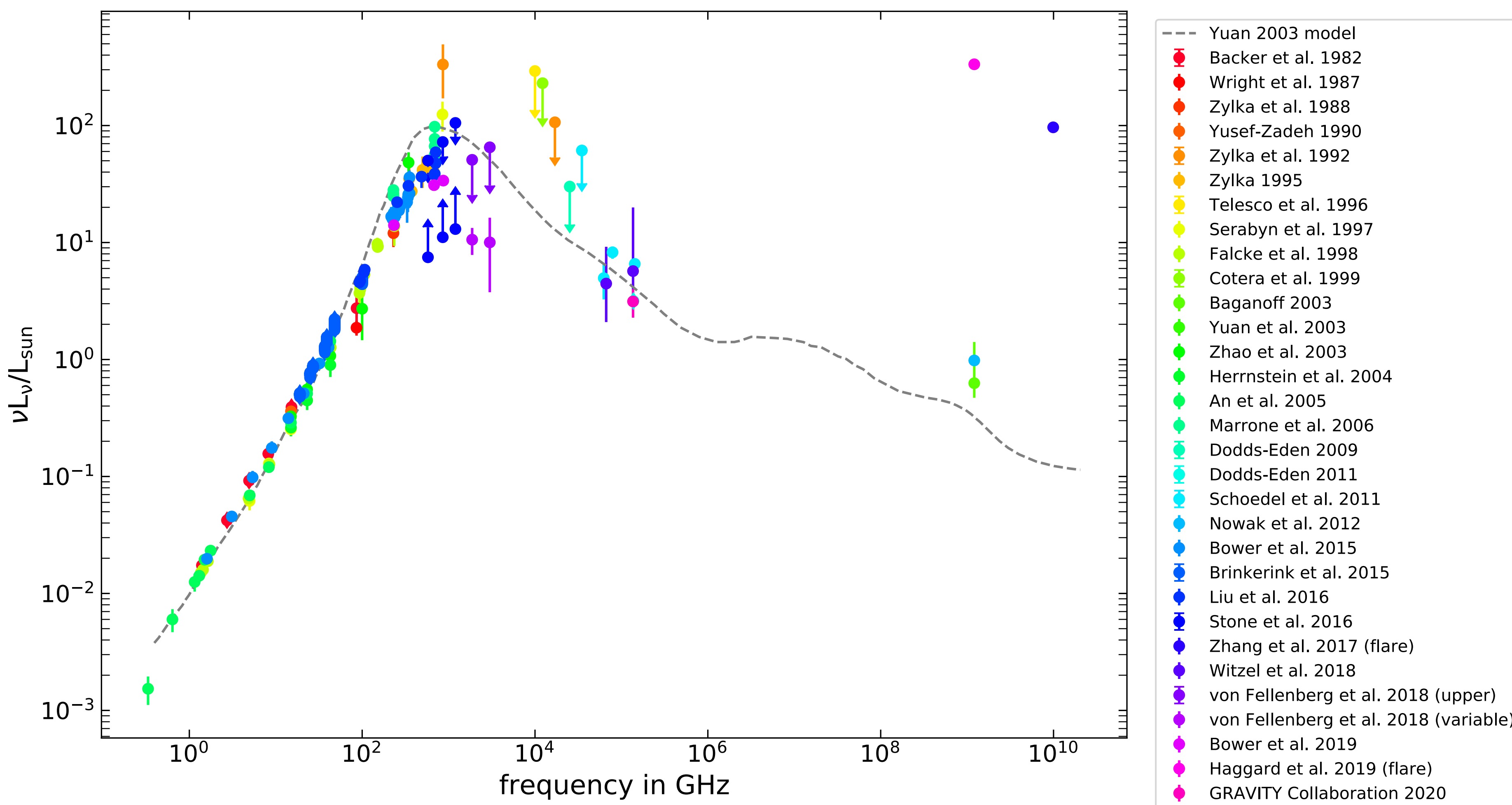


NIR-flare 2007

Movie: Rainer Schödel

Not your standard SMBH

- **Observations towards the GC are difficult (25 mag of extinction in the optical)**
- **Sgr A* has not obvious jet**
- **Sgr A* is under-luminous with orders of magnitudes below Eddington luminosity:**
  - at the Bondi radius ($10^5 R_S$ = 0.04 pc) $\dot{M}_{\rm Bondi} \sim 3 \times 10^{-6} M_\odot {\rm yr}^{-1}$
  - at 10% efficiency $\dot{M}_{\rm Bondi}$ would yield 10^4 times the observed bol. luminosity
  - Polarisation measurements: at R_S we find $\dot{M}_{\rm horizon} \sim 10^{-9}$ to $10^{-7} {\rm M}_\odot {\rm yr}^{-1}$



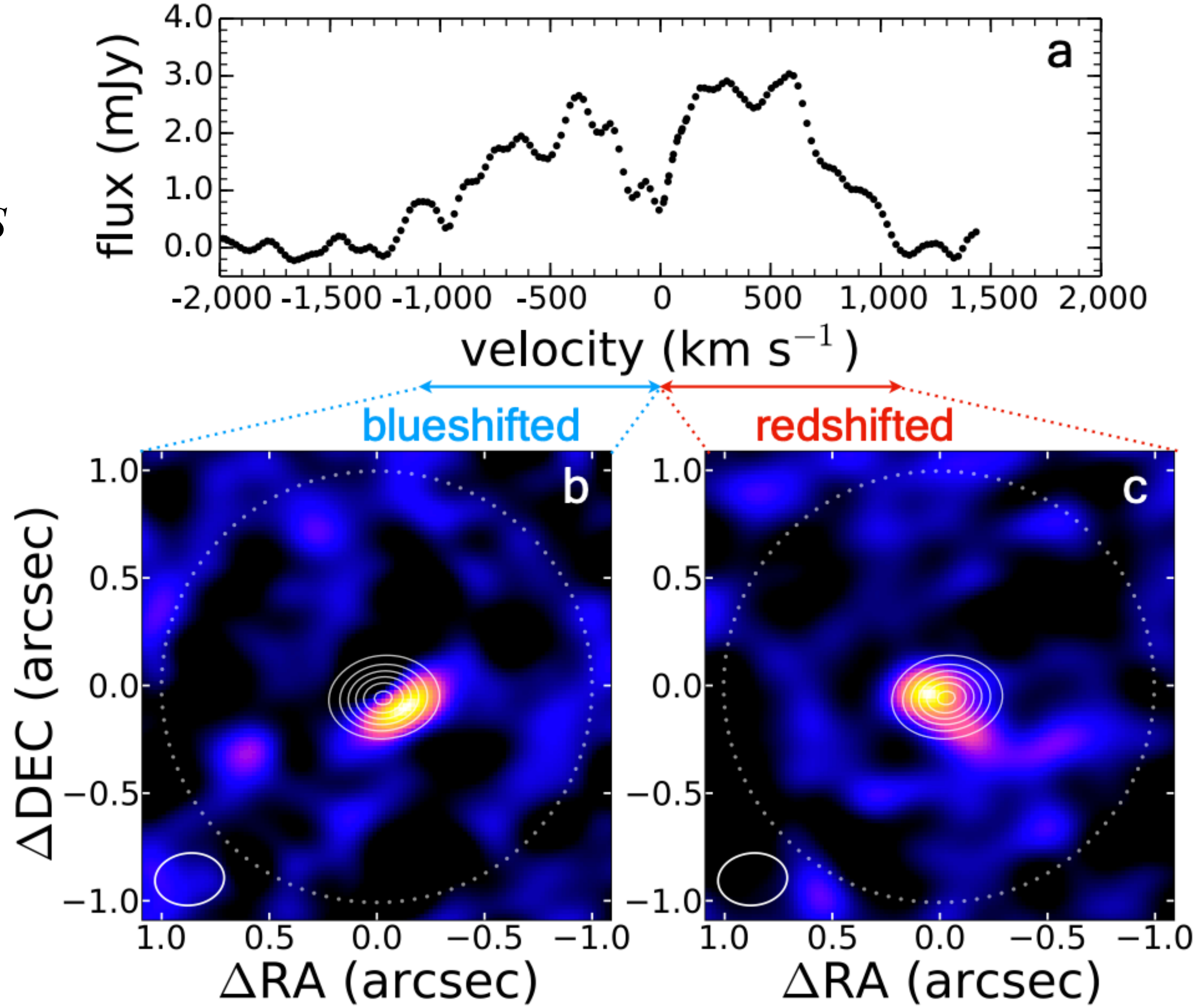
A 10^4 K disk detected in H30α

ALMA 231.9 GHz

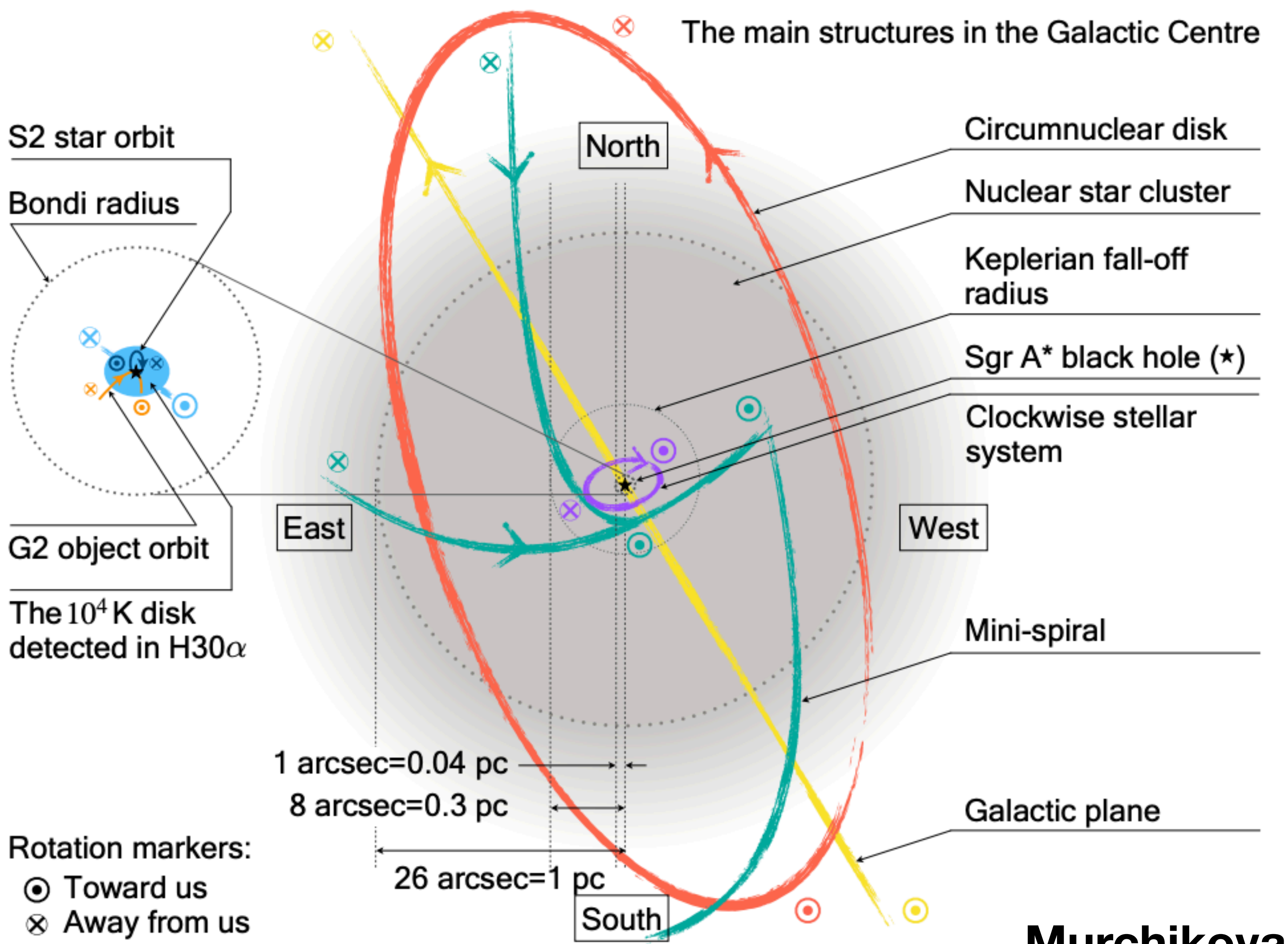
Murchikova et al. 2019

$n = 10^6 \text{ cm}^{-1}$

Within $2 \cdot 10^4 R_S$

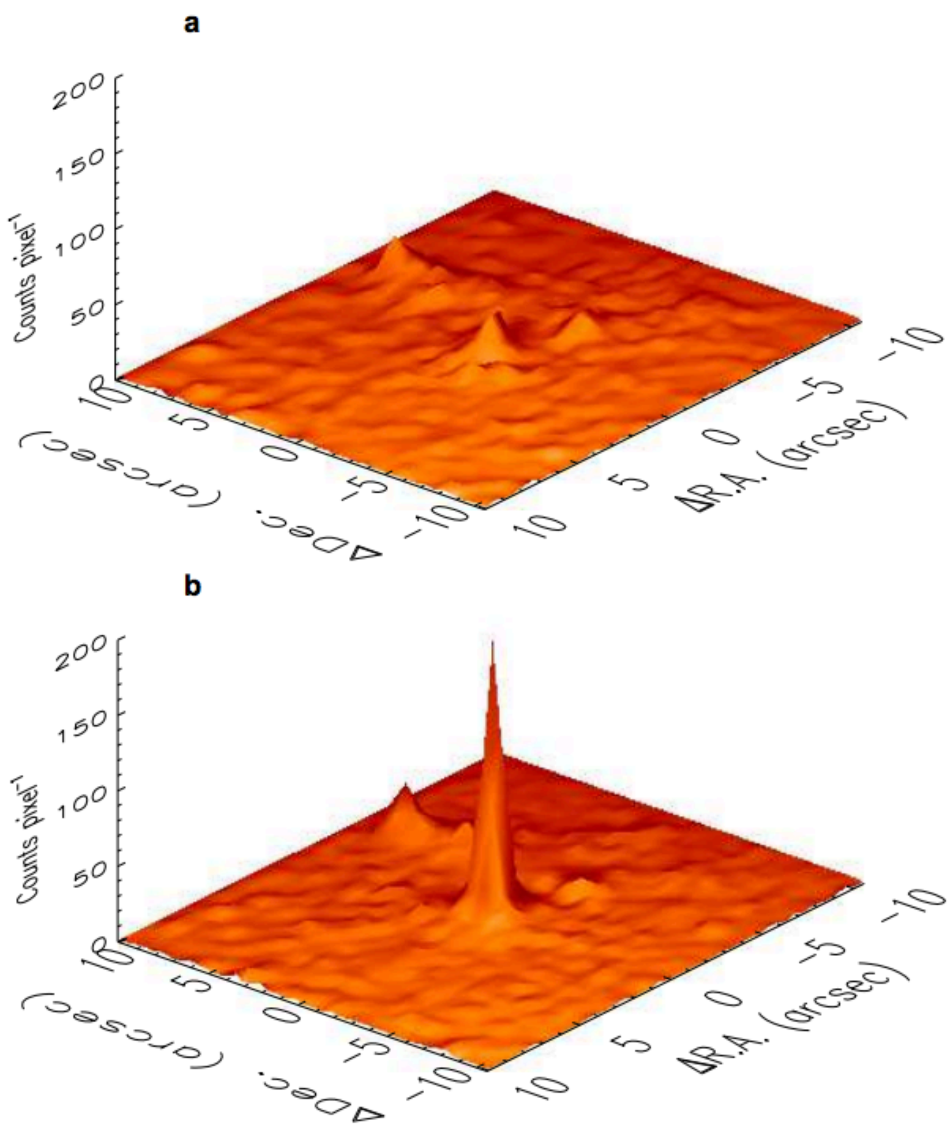


The Galactic Center

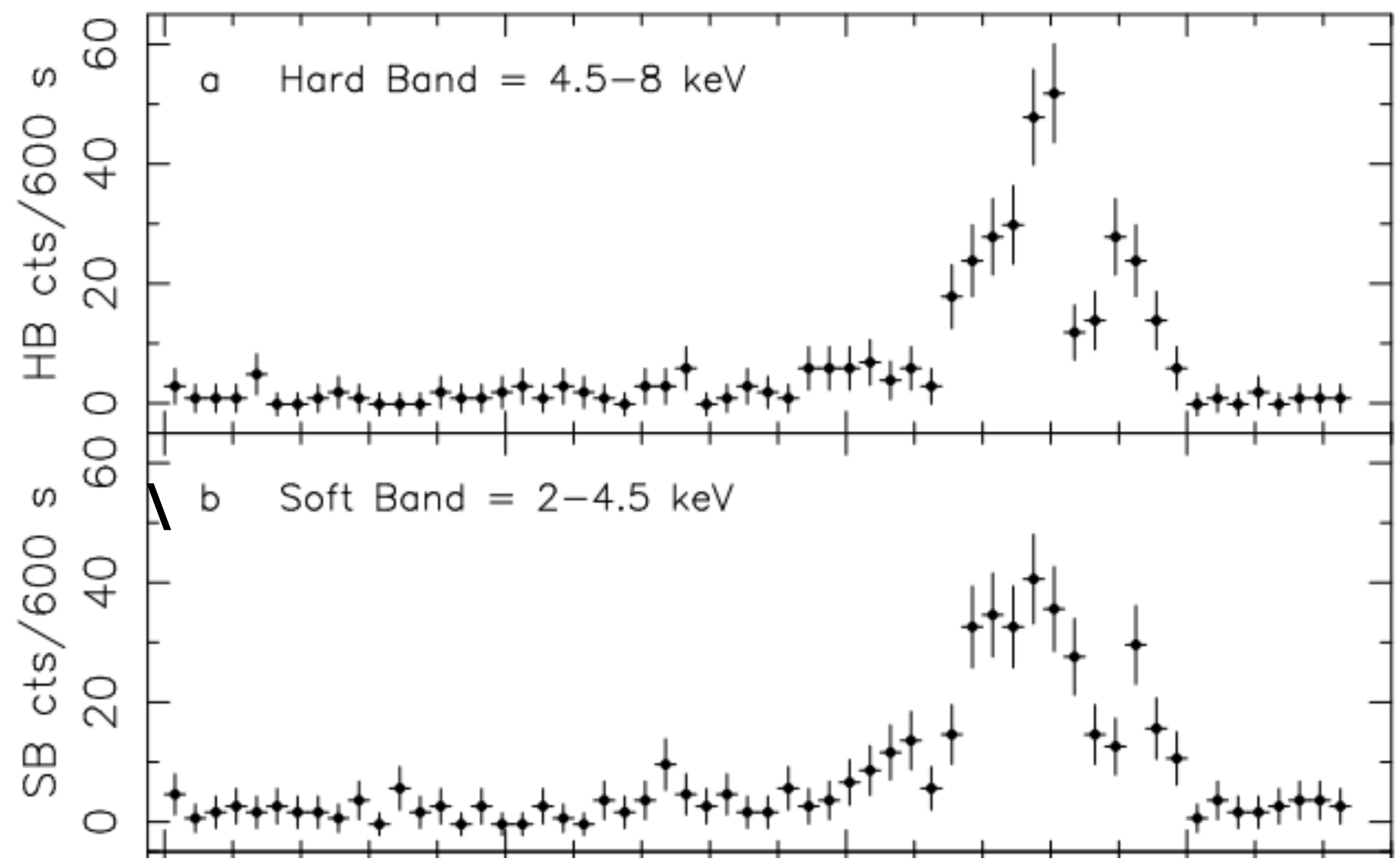


Murchikova et al. 2019

X-ray discovery paper



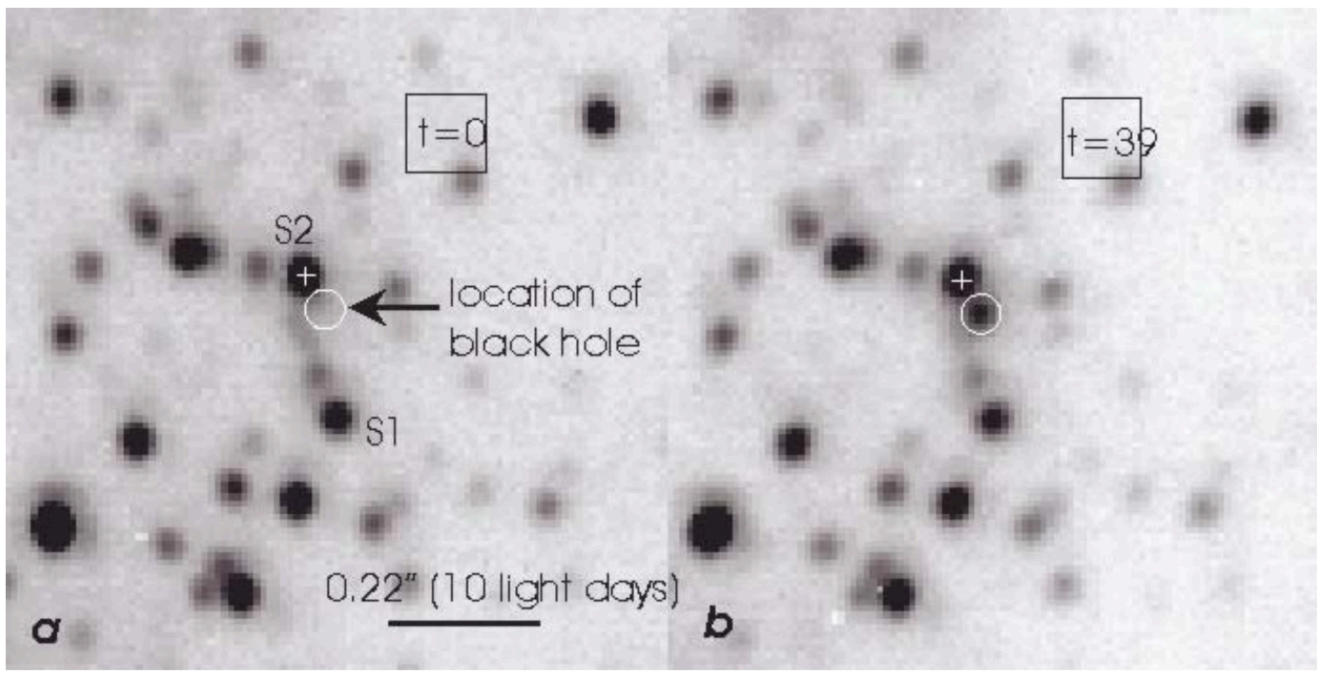
Baganoff et al. 2001, Nature



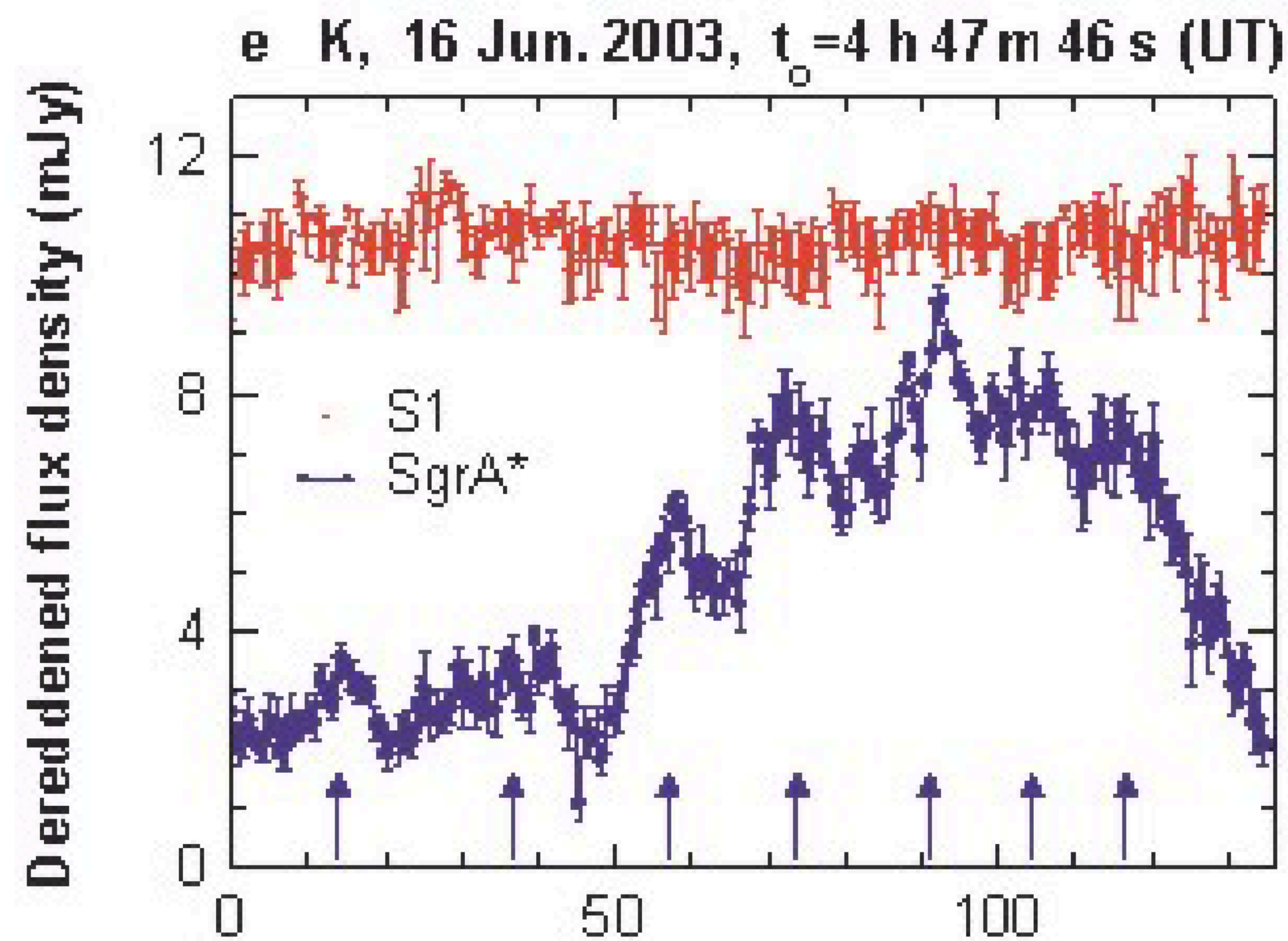
Main statement: X-ray flare associated with the SMBH, probably generated by SSC

NIR discovery papers

Genzel et al. 2003, Nature



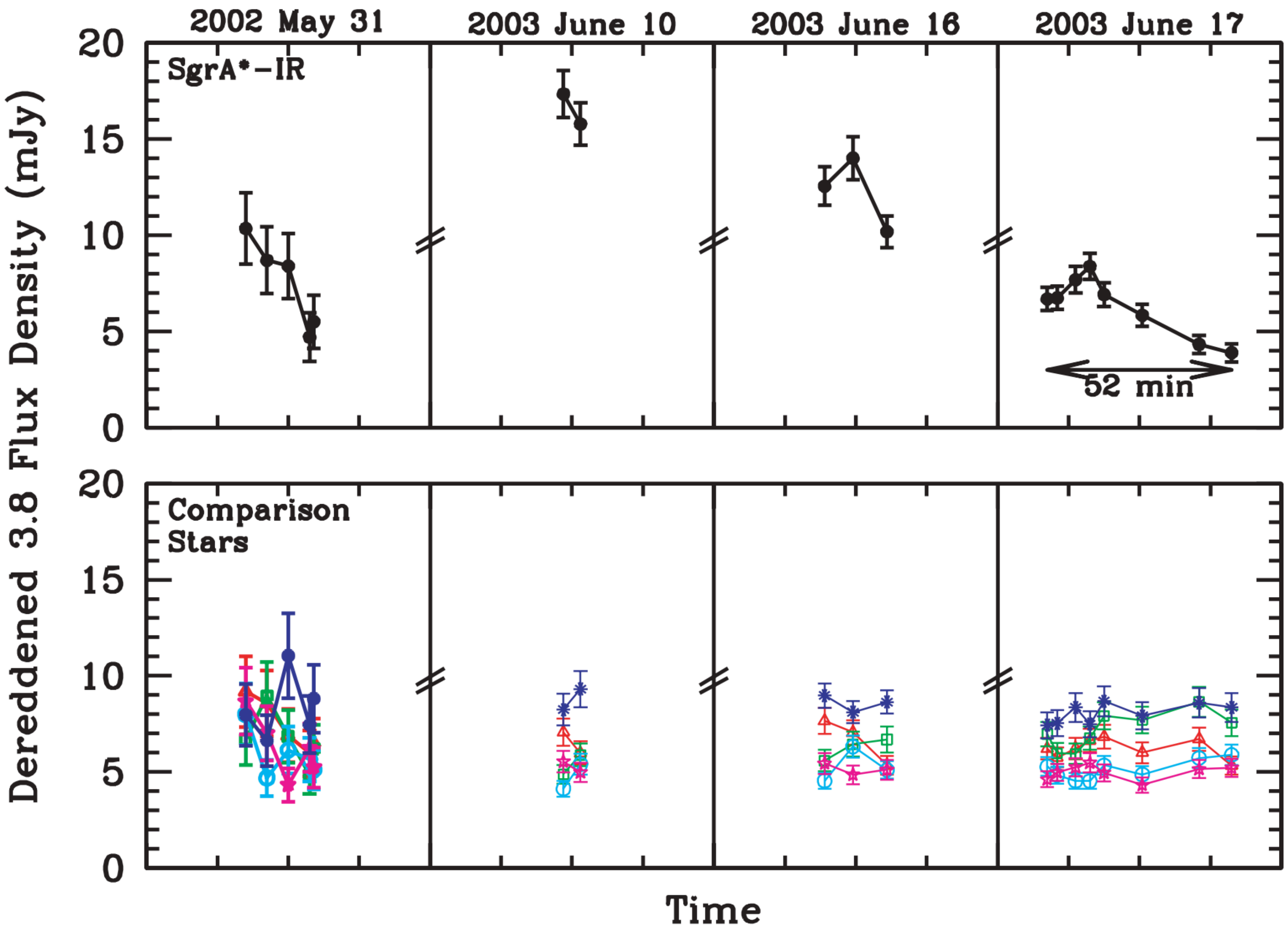
VLT/NACO H-band



VLT/NACO K-band

NIR discovery papers

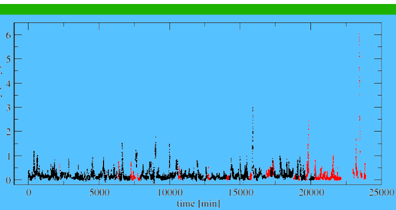
Ghez et al. 2004



Main statements

Genzel et al. 2003, Nature

- **Detection of flares of a factor 5**
- **Detection of quiescent level**
- **Flares last 30-100 minutes**
- **rise/decay times of 2-10 minutes**
- **Quasi periodicity around 20 minutes, but perhaps red noise**
- **Sgr A* much redder than the surrounding stars**
- **Potentially tendency to become bluer when brighter**
- **SED and radiative mechanisms proposed:**
    - **low flux densities fit SED extrapolated from submm**
    - **Flares must be different process like synchrotron from magnetic reconnection in turbulent plasma**



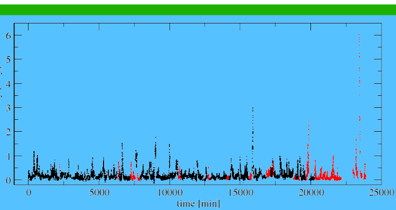

Why study Sgr A* variability?

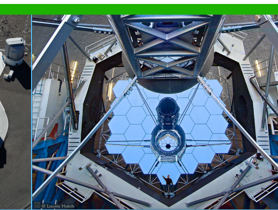
Sgr A* R_S = 0.08 AU

10 light min = 1.2 AU or 15 R_S

Dodds-Eden+09: Factor 2 in $\Delta t < 47$ seconds corresponding to ~1.2 R_S

Do+19: Factor 9 in $\Delta t < 2$ min corresponding to ~3 R_S

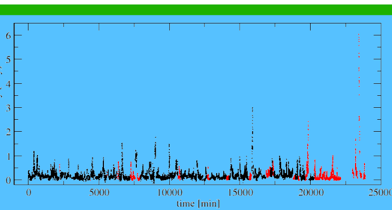


Publications since 2001 on **observing or modeling** IR, X-ray, and submm data: > **60 papers**

Categories:

- **Statistical analyses of flux densities and timing properties**
- **Multi-wavelength observations and SED modeling**
- **NIR spectral index measurements**
- **NIR polarization and relativistic modeling**
- **GRAVITY**




Spitzer/IRAC and *Chandra* Observations of Sgr A*

Max-Planck-Institut für Radioastronomie

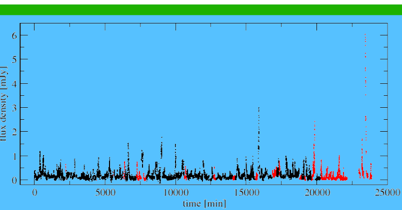
Gunther Witzel

Greg Martinez
Mark Morris
Eric Becklin
Andrea Ghez
Tuan Do

Steven Willner
Giovanni Fazio
Joe Hora

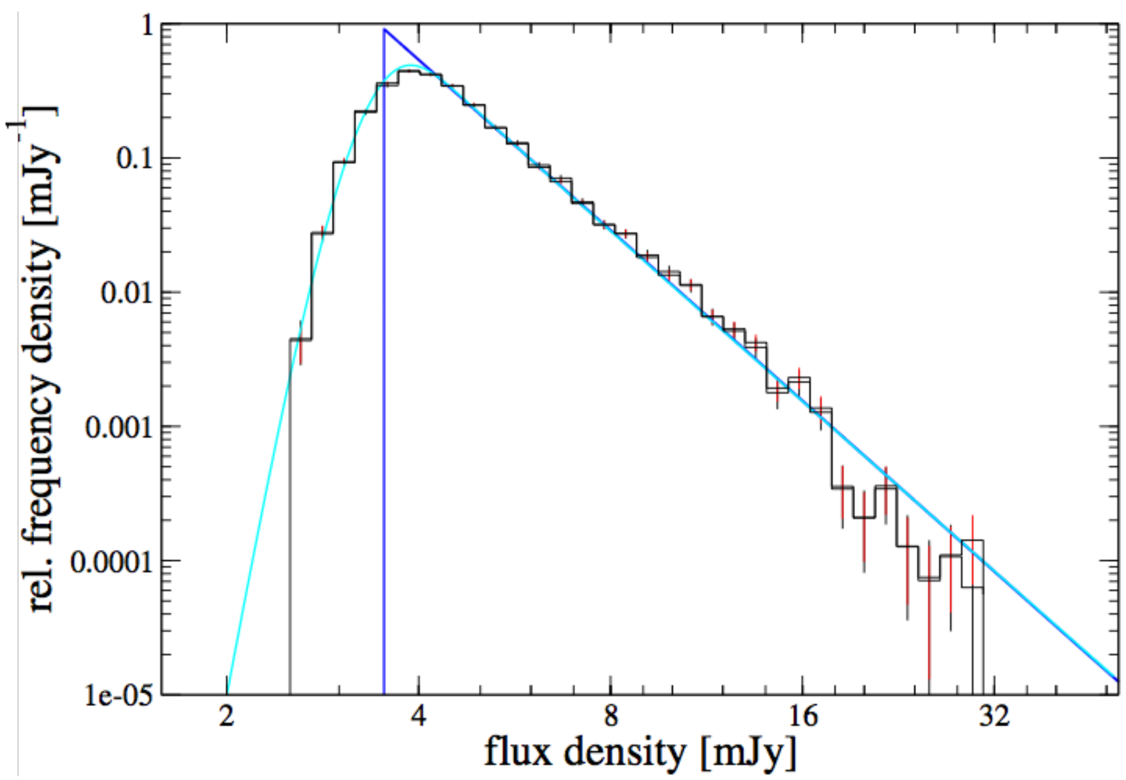
Charles Gammie

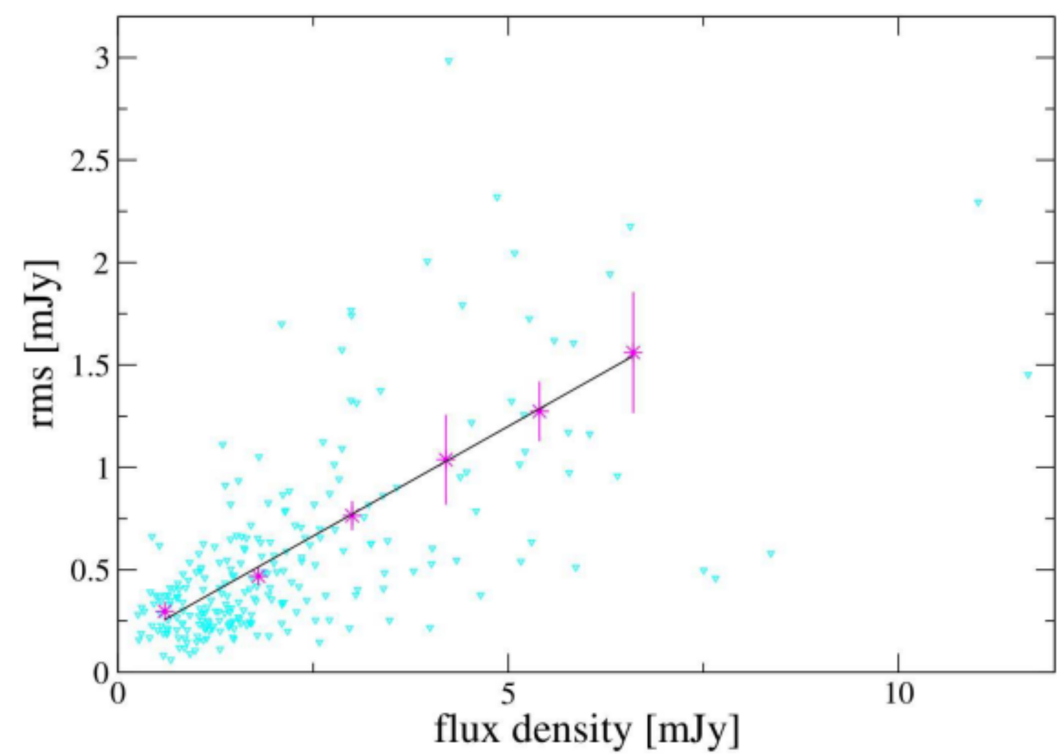
Fred Baganoff, Daryl Haggard, Hope Boyce, Howard Smith,
Joey Neilsen, Sera Markov,
Dan Marrone, Gabriele Ponti, Ramesh Narayan, **Zhiyuan Li**



2.2μm
VLT
KECK
F [mJy]
4.5μm
SPITZER
F [mJy]
2-8 keV
HETG/ACIS-S
F [cts s^-1]
2-8 keV
ACIS-I
ACIS-S
F [cts s^-1]
345 GHz
APEX
SMA
230 GHz
SMA
ALMA
F [Jy]
time [min]

Power-law model for NIR flux density distribution

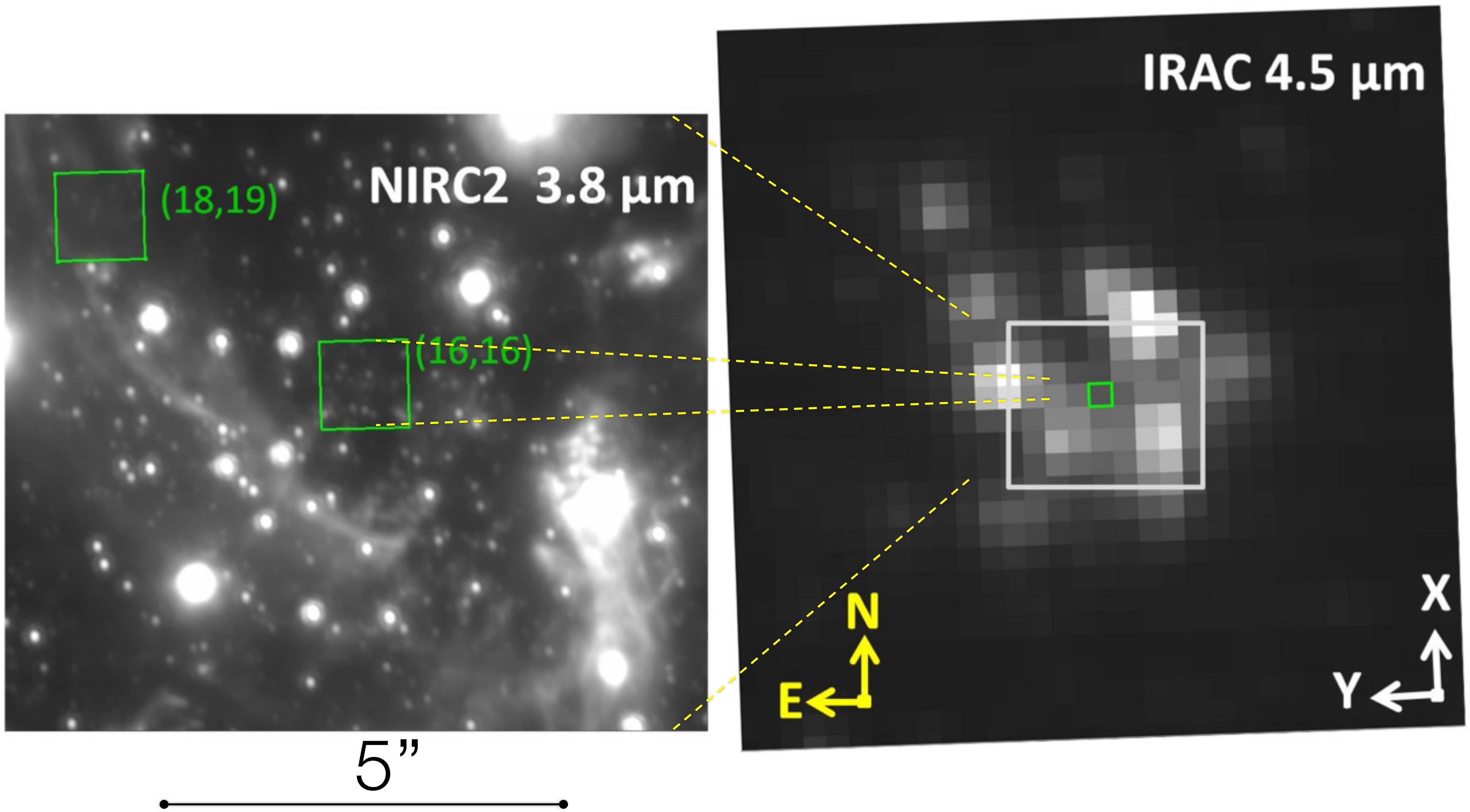




flux-rms relation

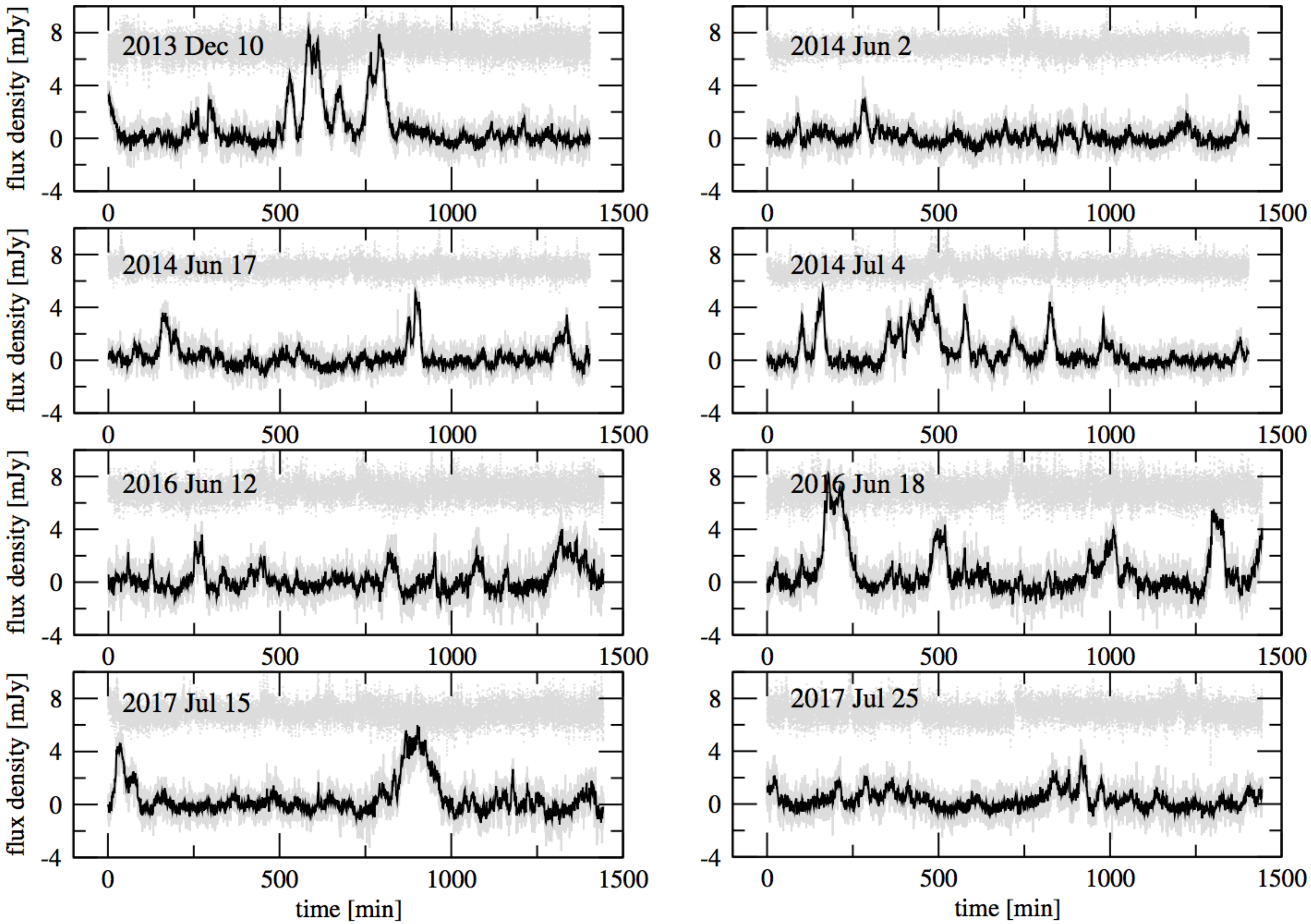
Witzel et al. 2012

IRAC/Spitzer 4.5 um monitoring of Sgr A*



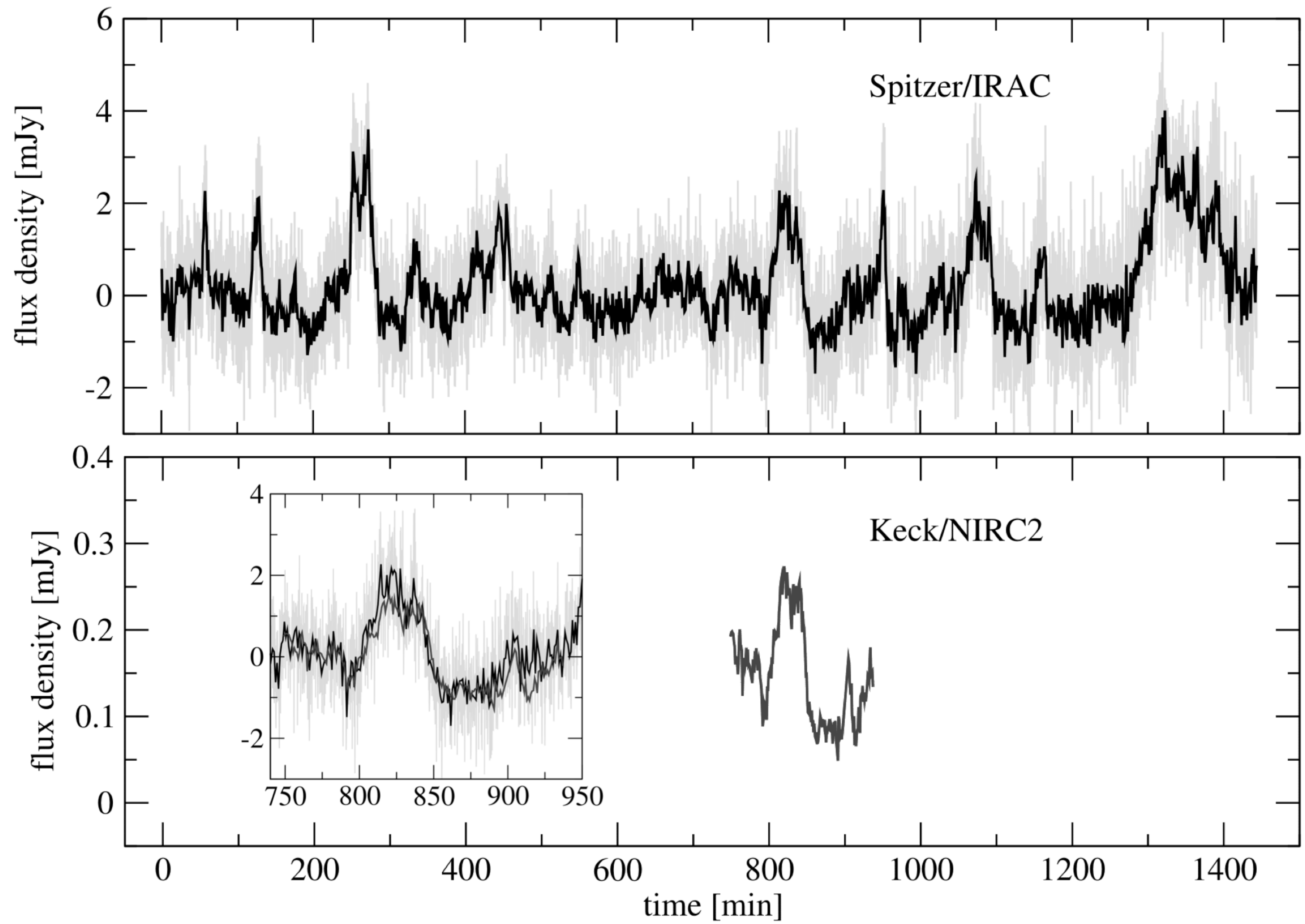
Hora, Witzel et al. 2014

Eight 24 hour light curves with Spitzer



Witzel+18

July 2016 Spitzer + Keck



Flux density ratio

M/K = 12.4

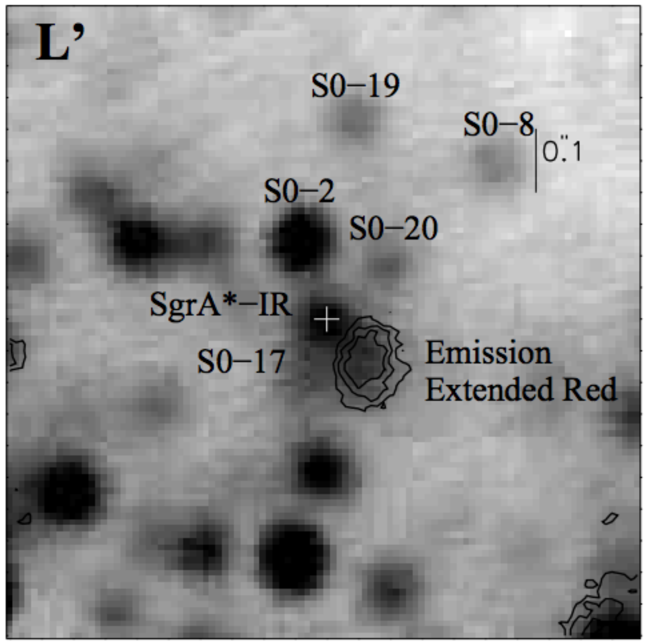
NIR spectral index

α = -1.7

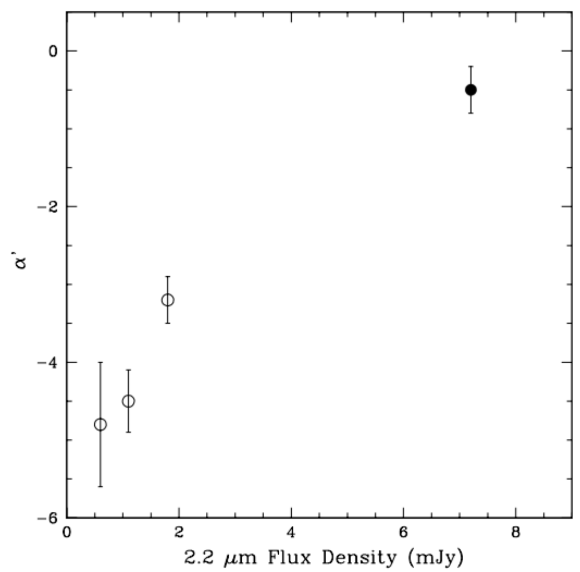
Witzel+18

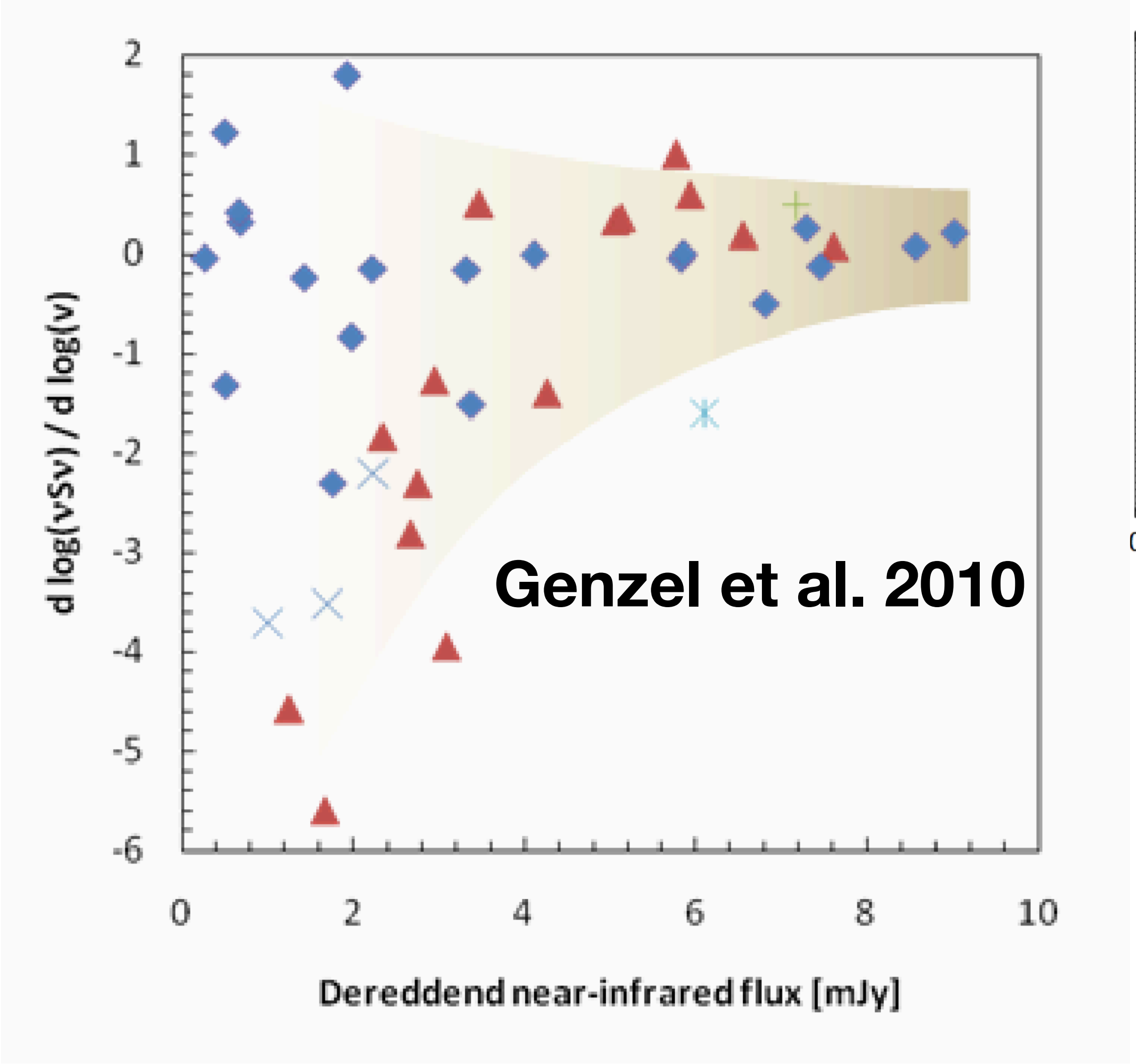
NIR spectral index

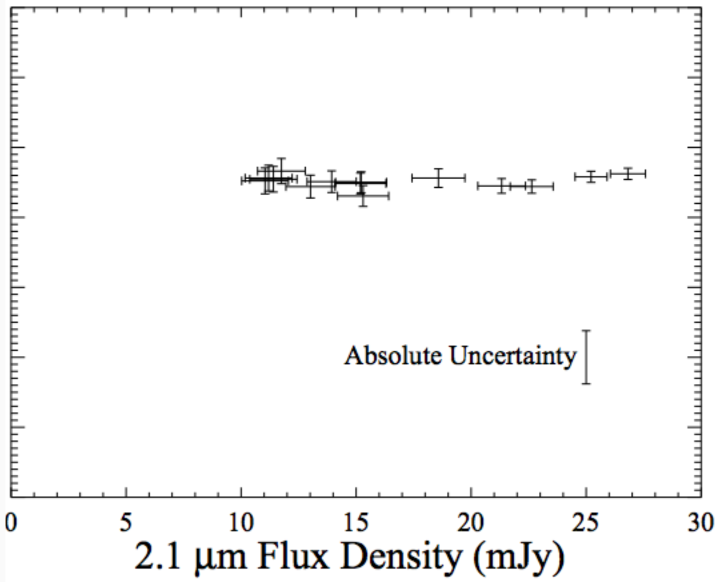
Eisenhauer et al. 2005, Ghez et al. 2005, Gillessen et al. 2006, Krabbe et al. 2006, Hornstein et al. 2007, Bremer et al 2011



Ghez et al. 2005



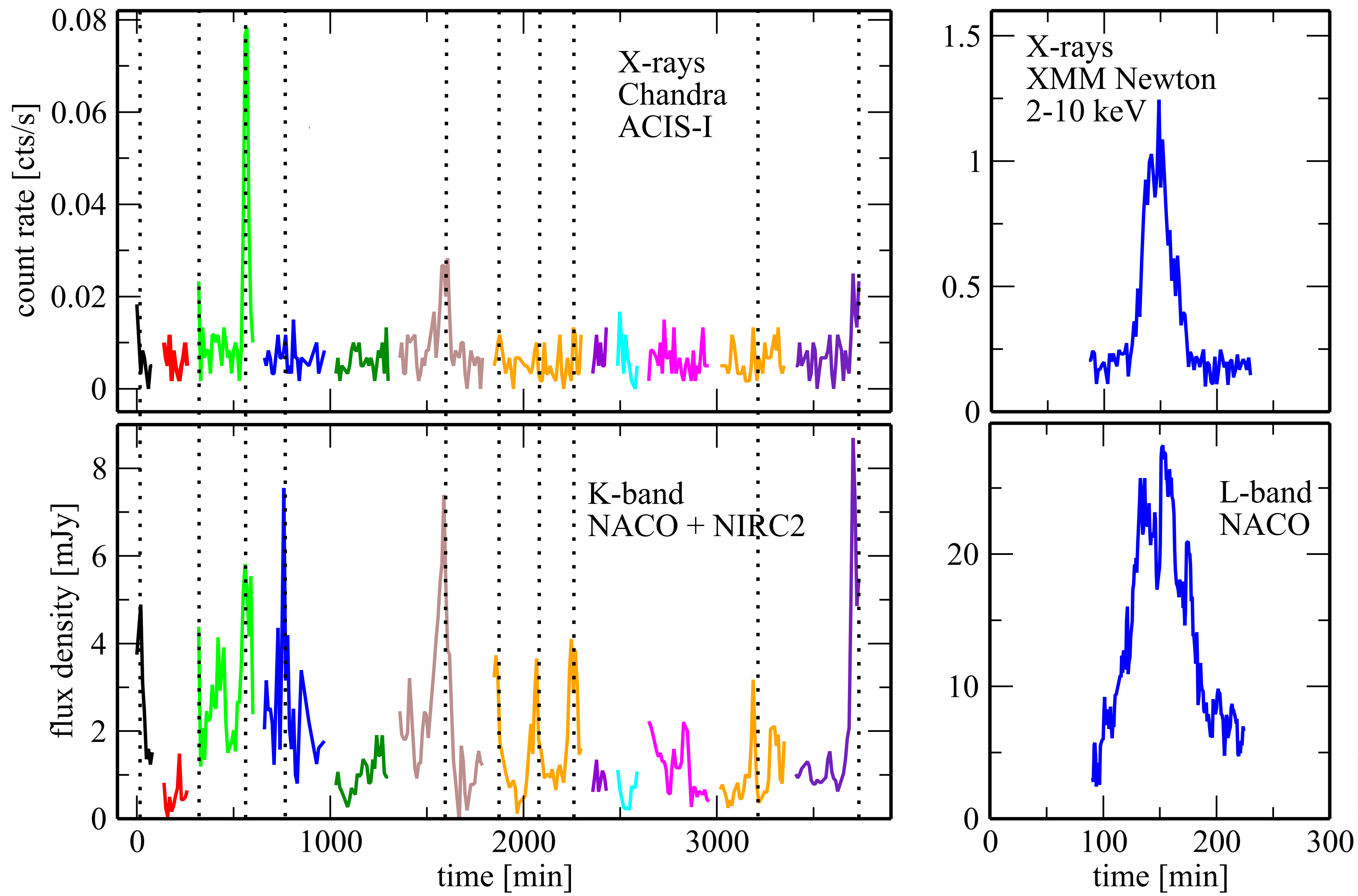




Hornstein et al. 2007

Fazio et al. 2018

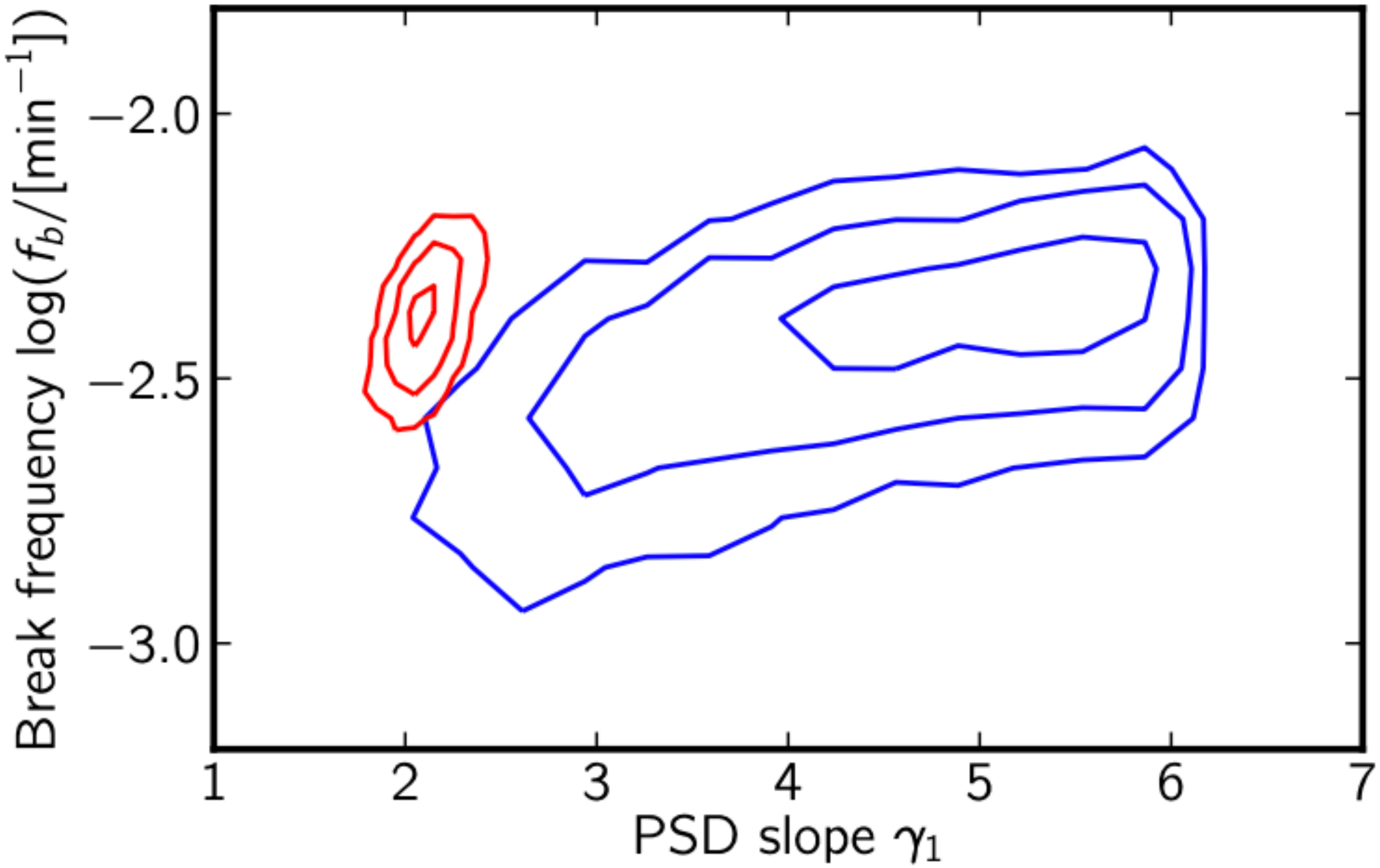
The correlation between X-ray and the NIR (K-band and L-band)



G. Fazio + 18

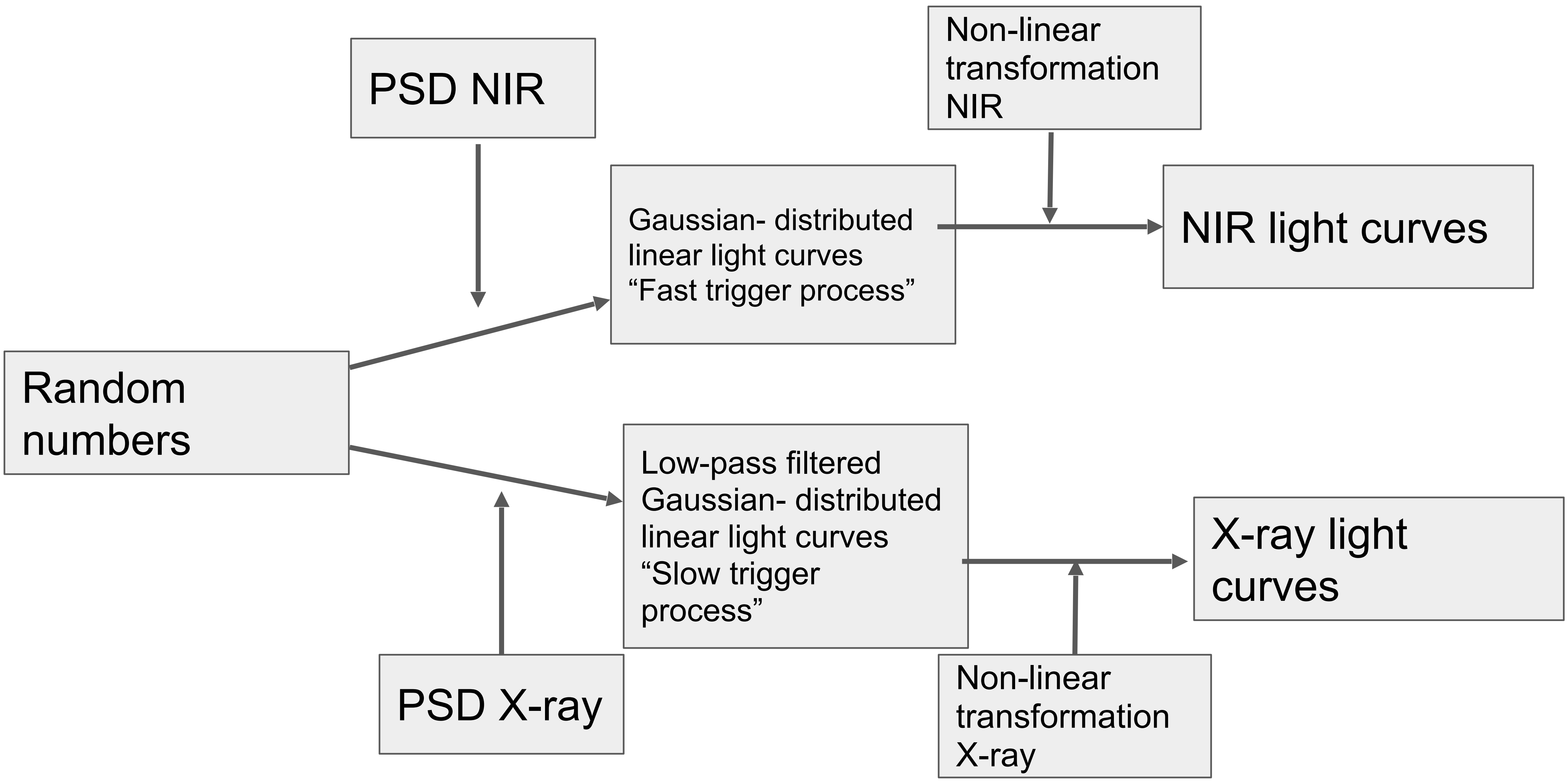
Dodds-Eden+09

PSD comparison NIR to X-ray



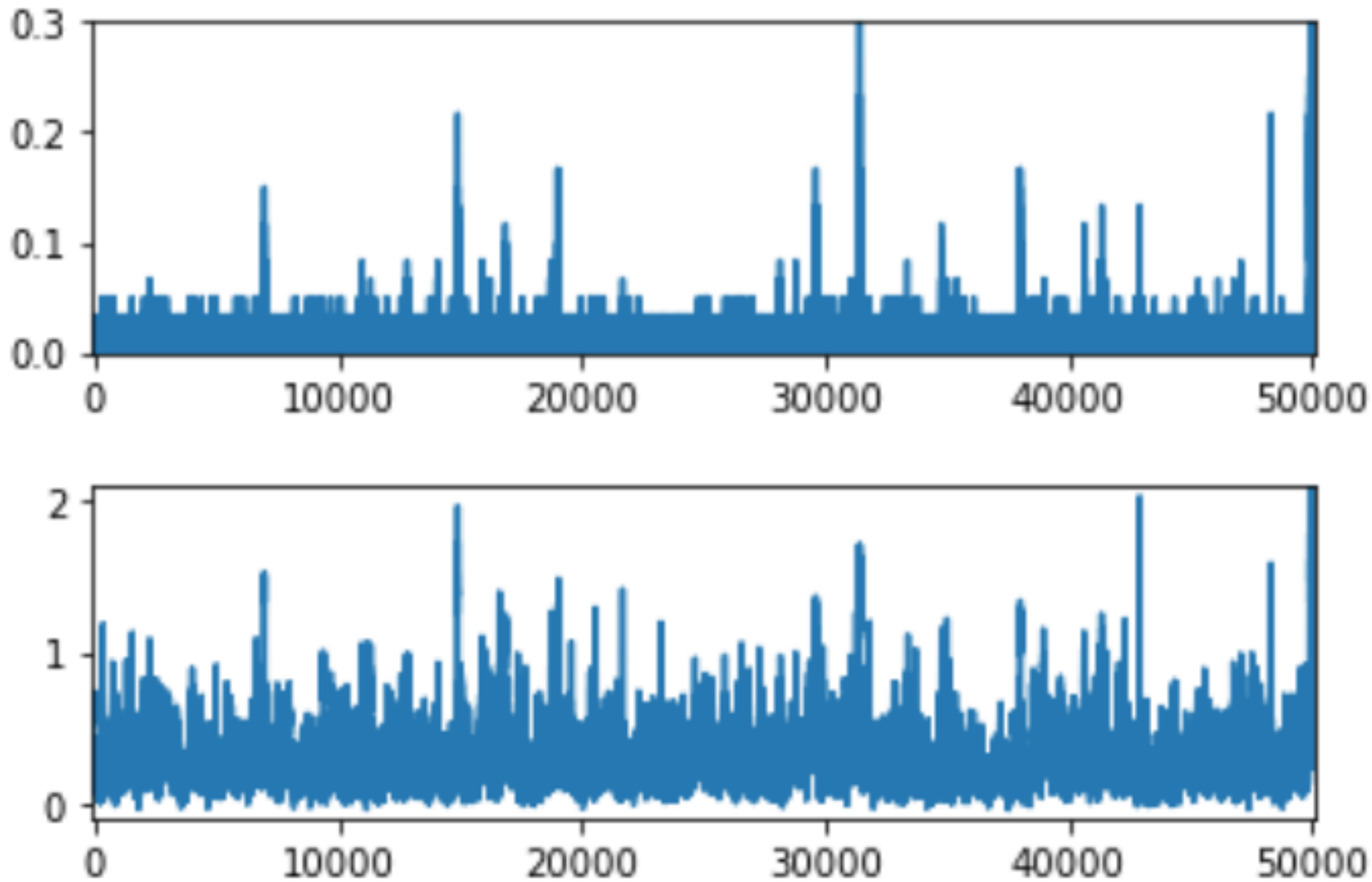
Witzel et al. 2018

Nature of correlation between X-rays and NIR



These light curves can fit all observed properties (simulations, generic example)

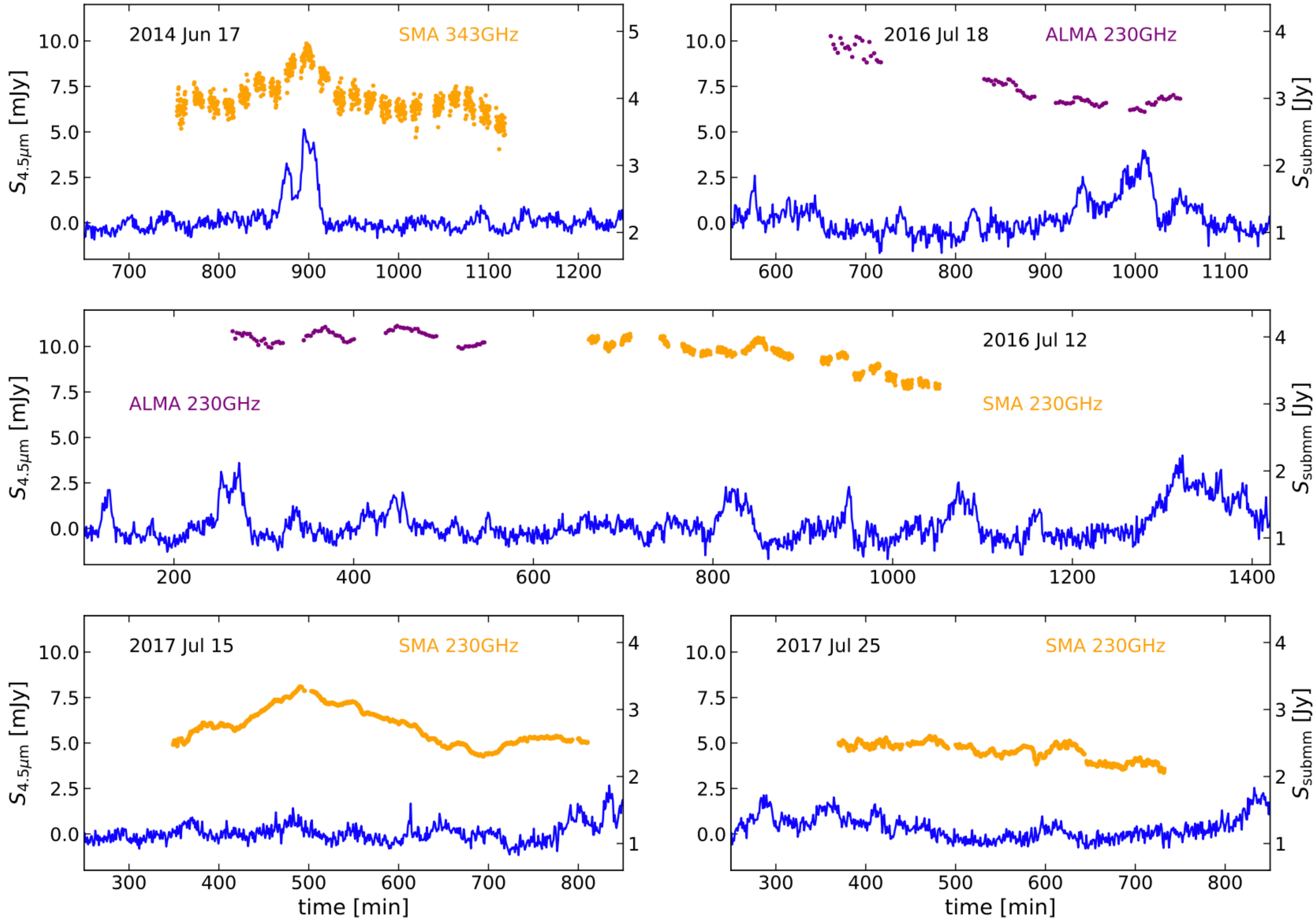
Witzel et al. 2018



X-rays

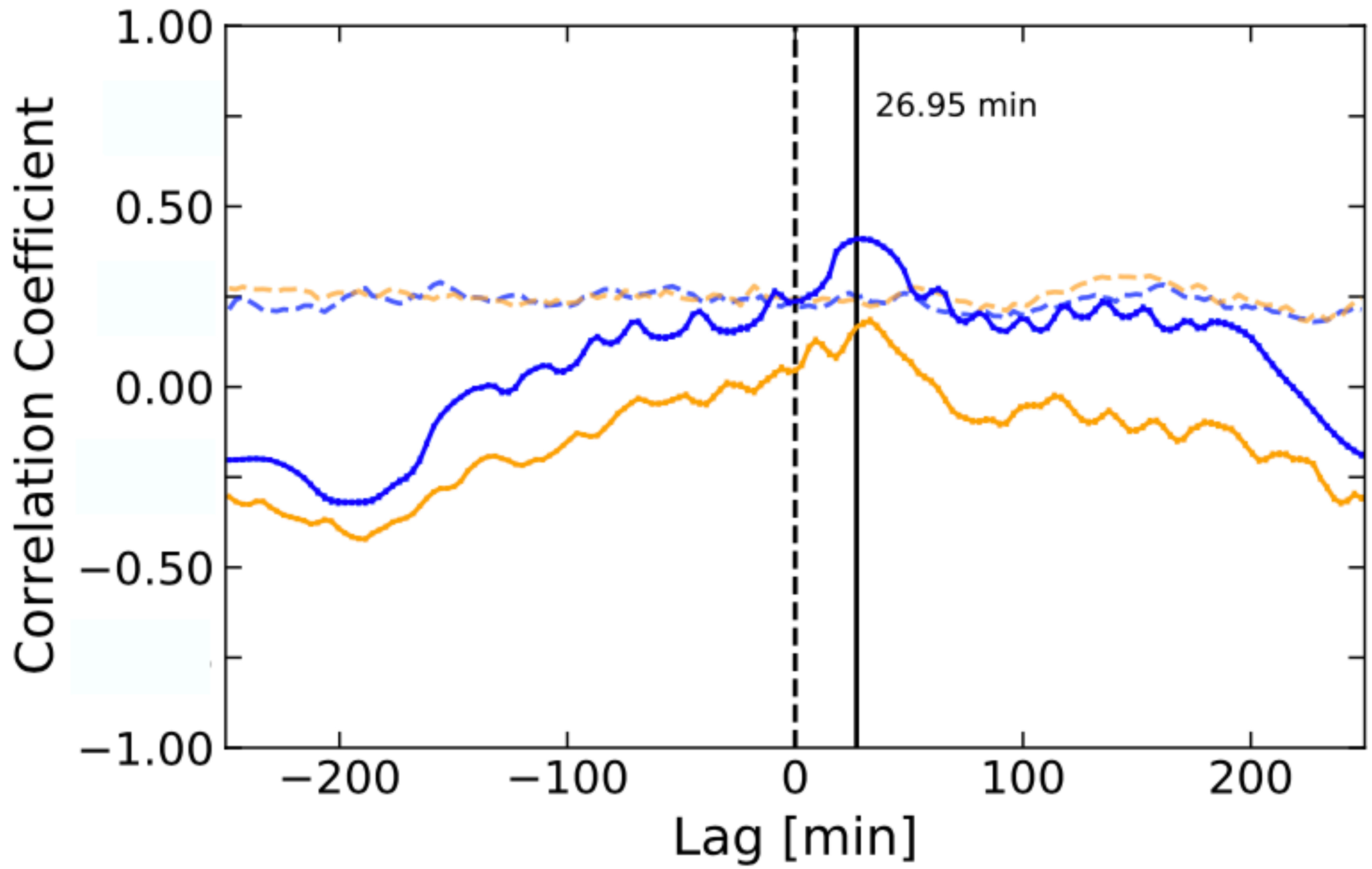
NIR

Submm - NIR (Spitzer) correlation



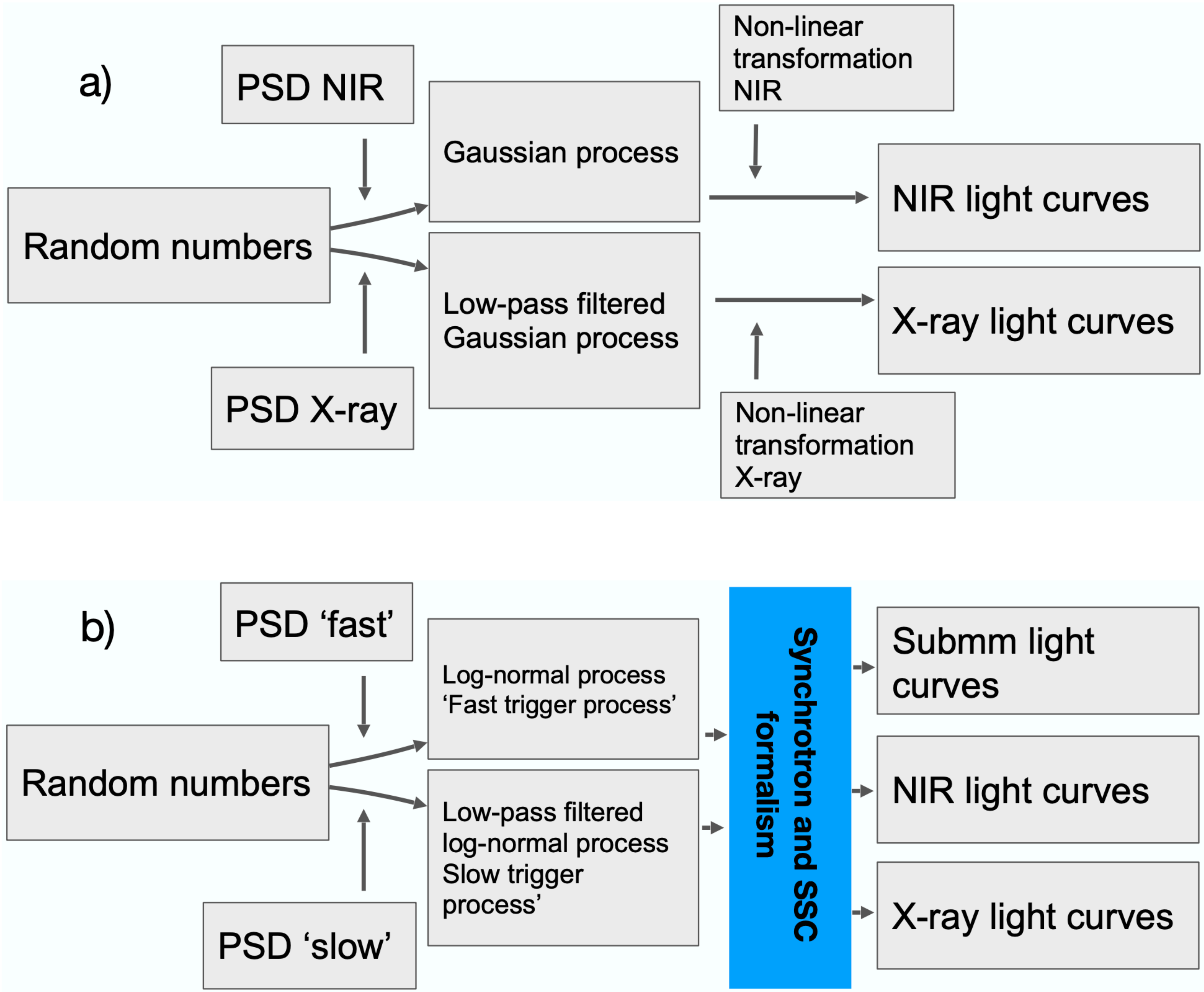
Witzel et al. 2021

Submm - NIR correlation

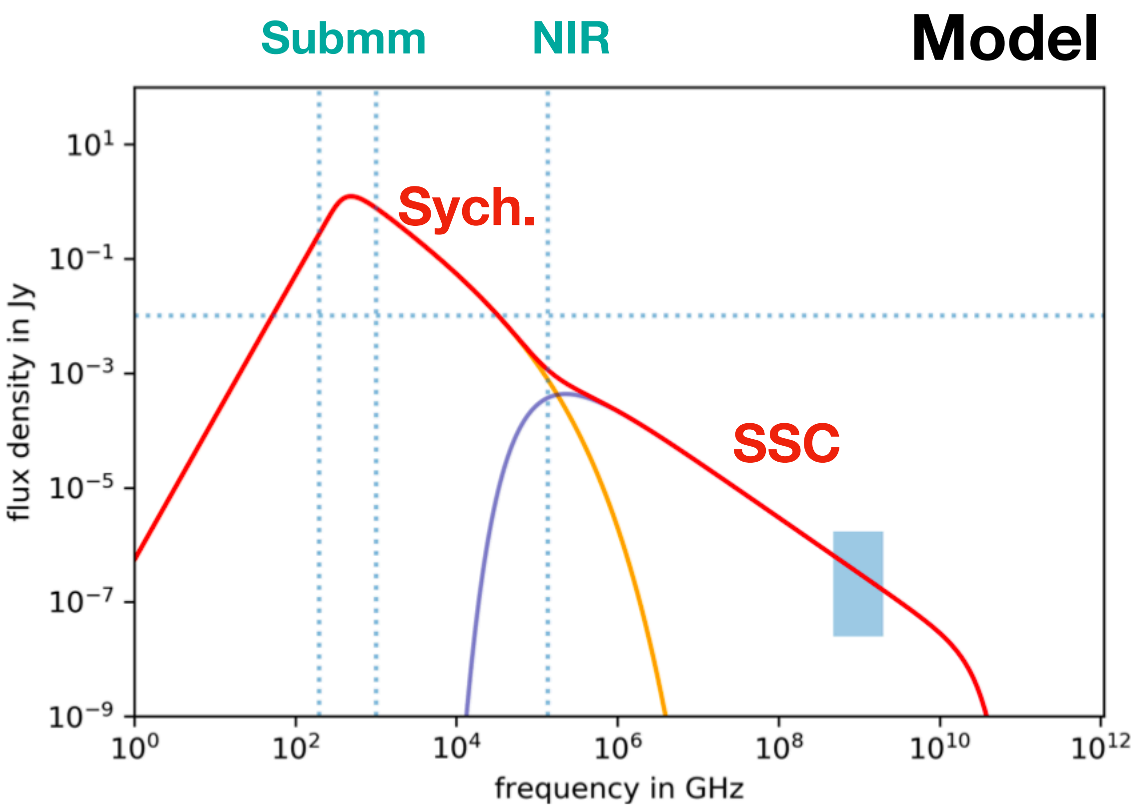


Witzel et al. 2021

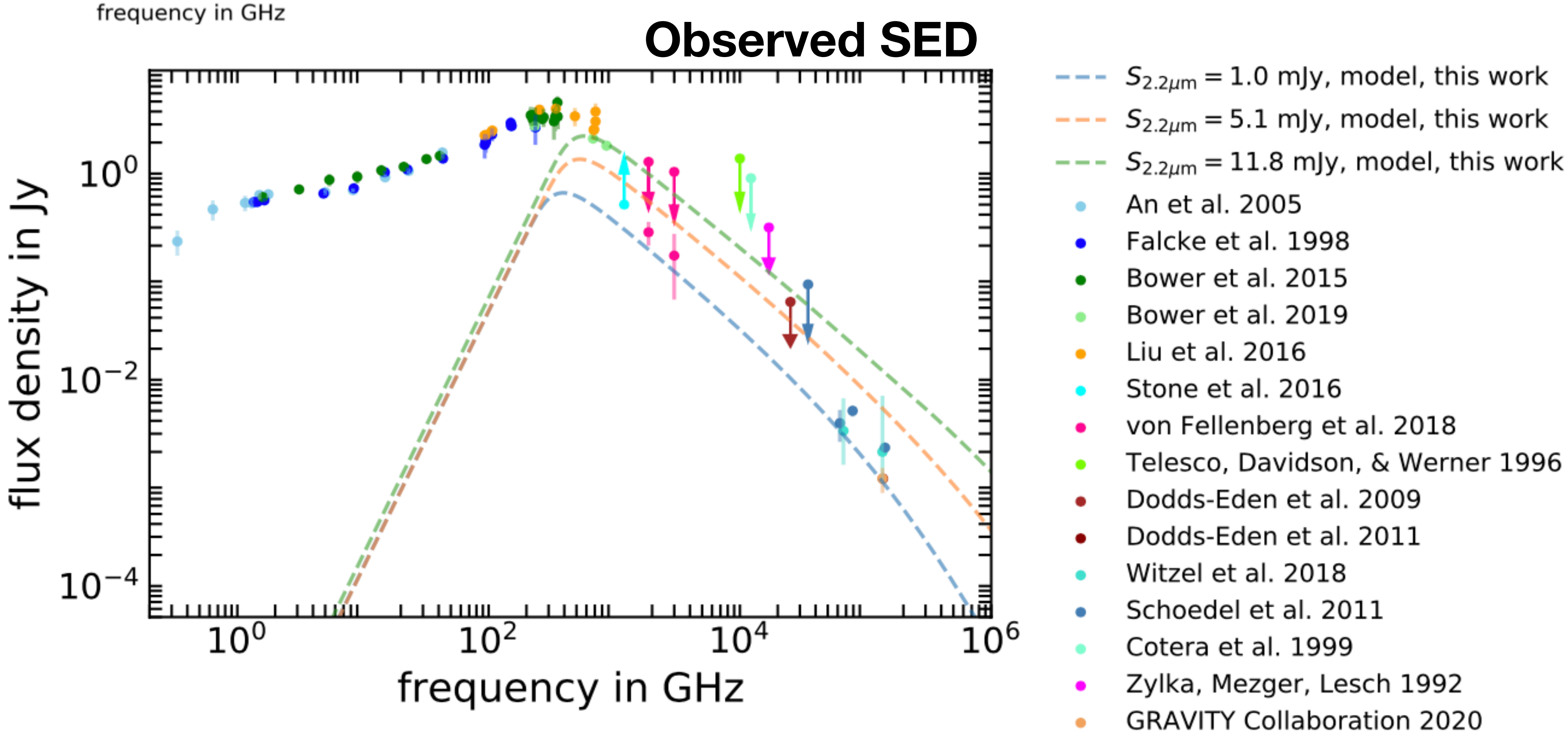
Stochastic/Physical model



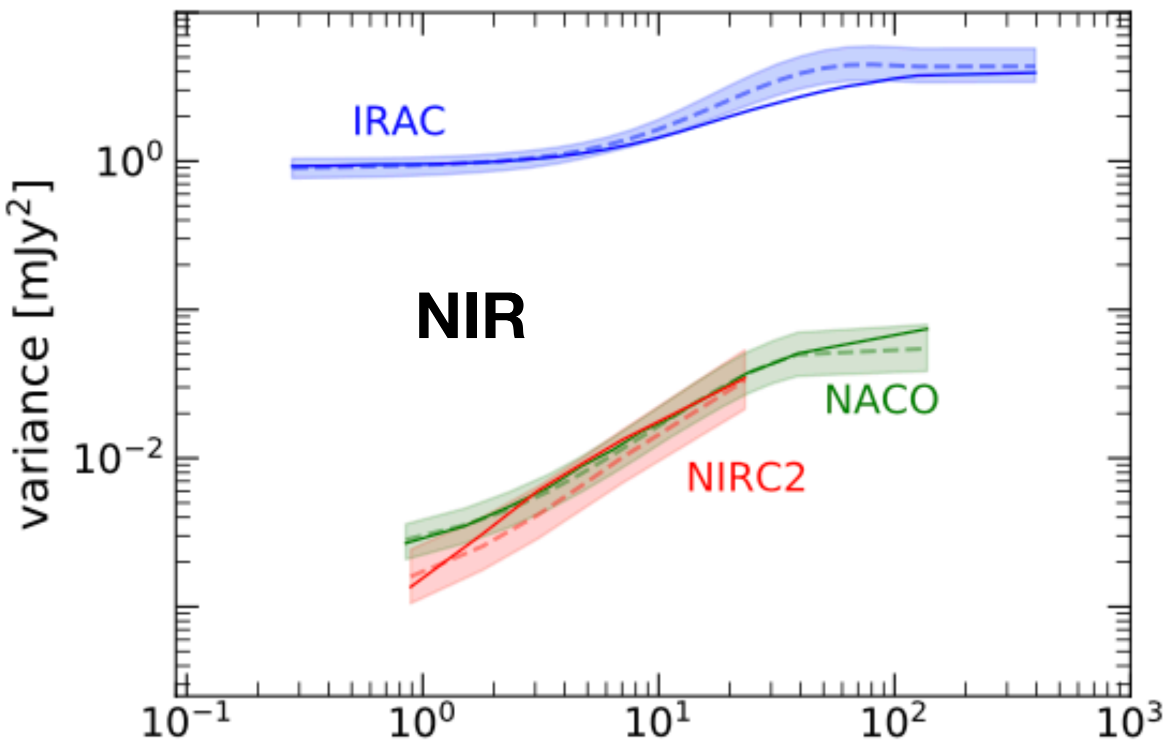
SED of compact component of Sgr A*

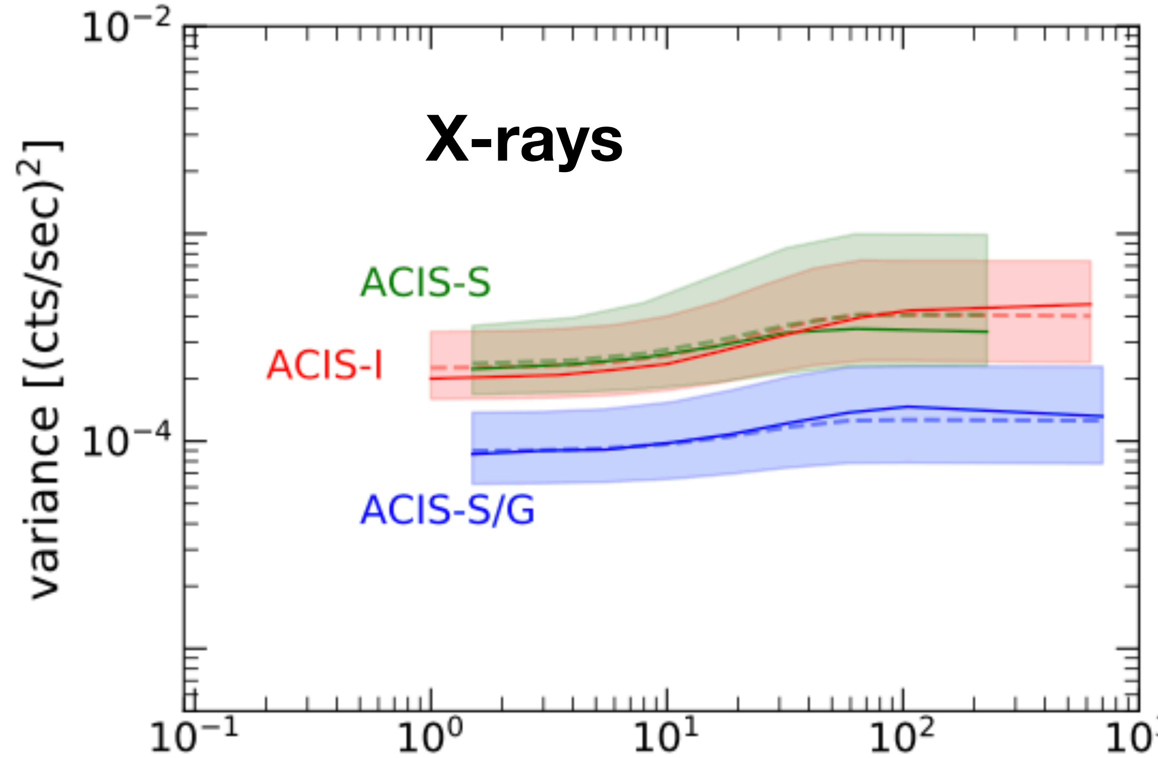


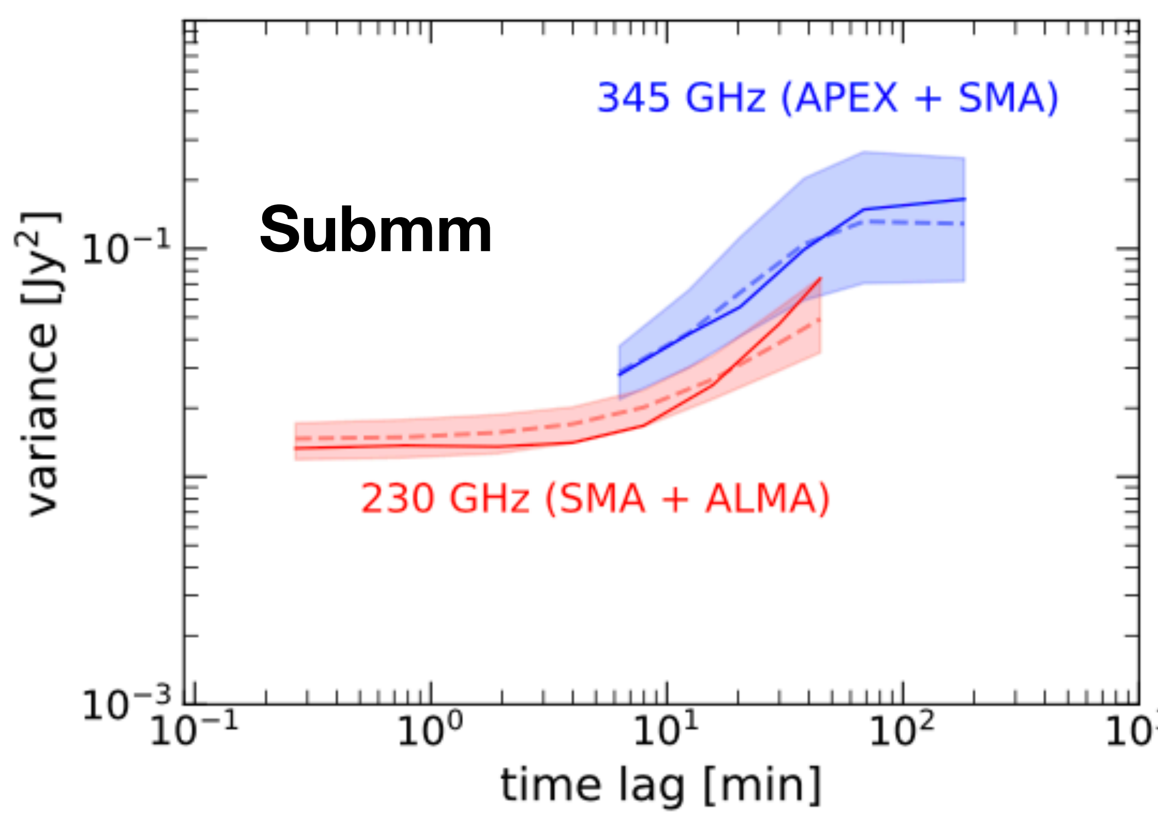
Witzel et al. 2018



Fitting structure functions

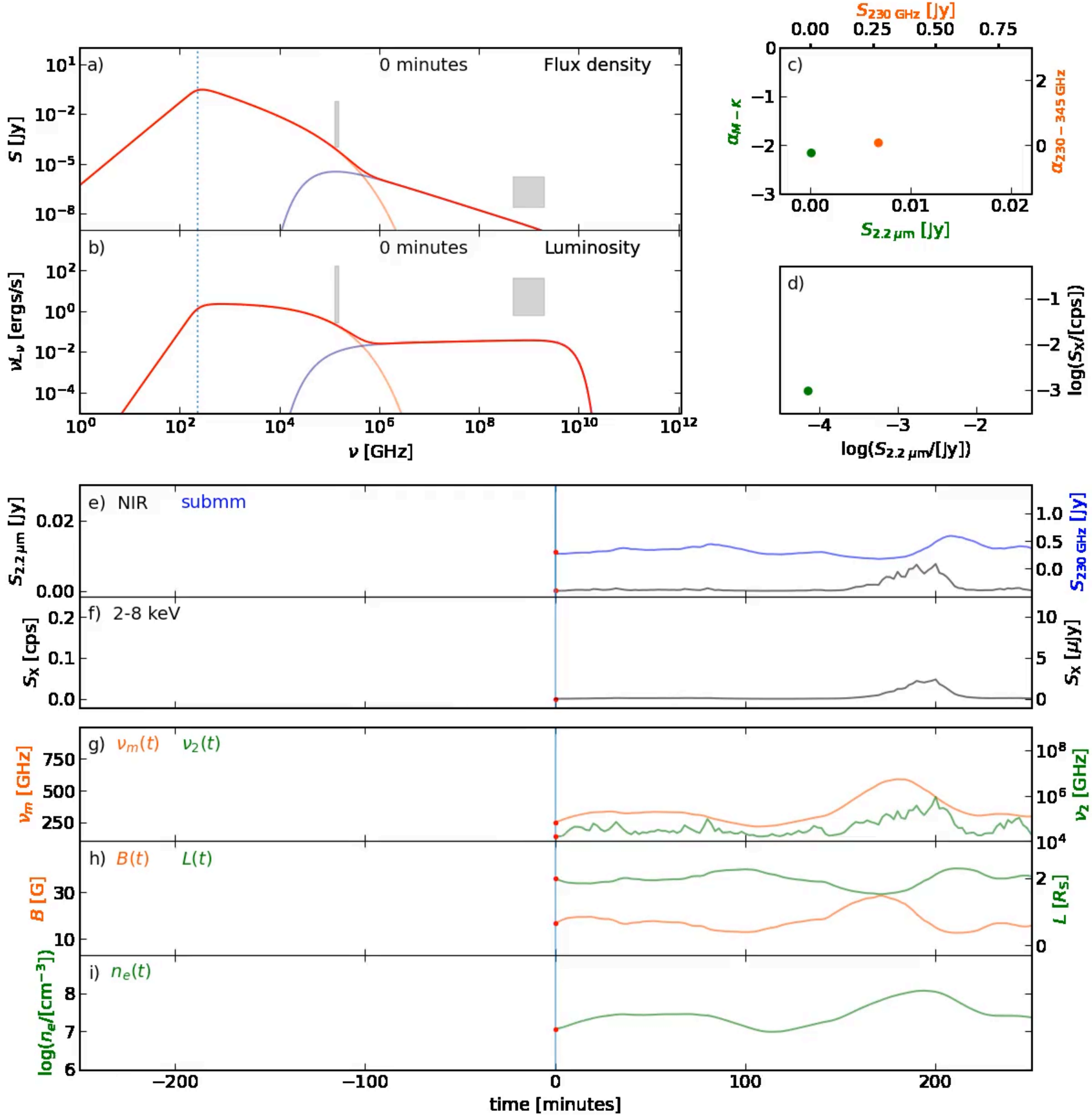




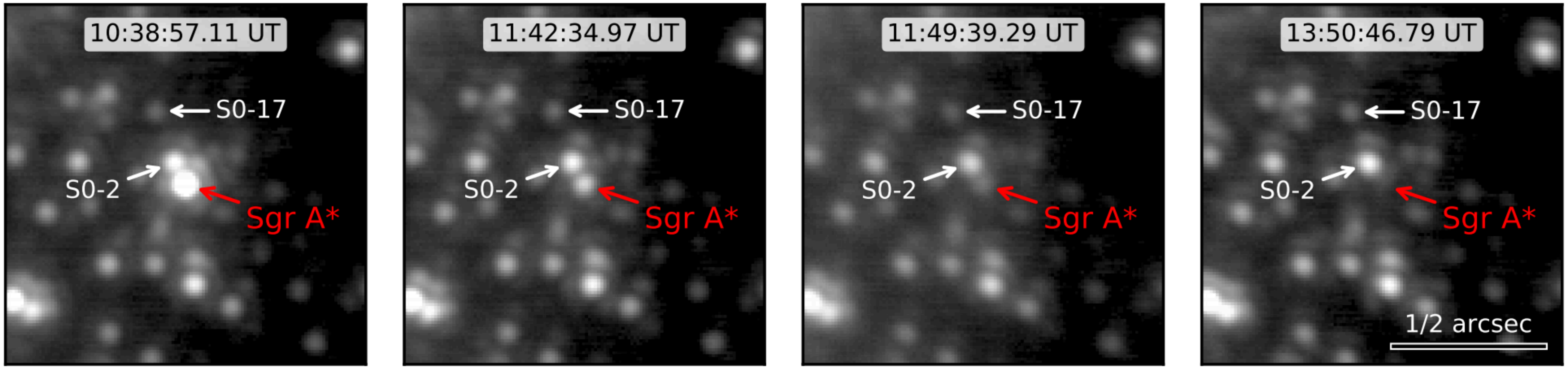


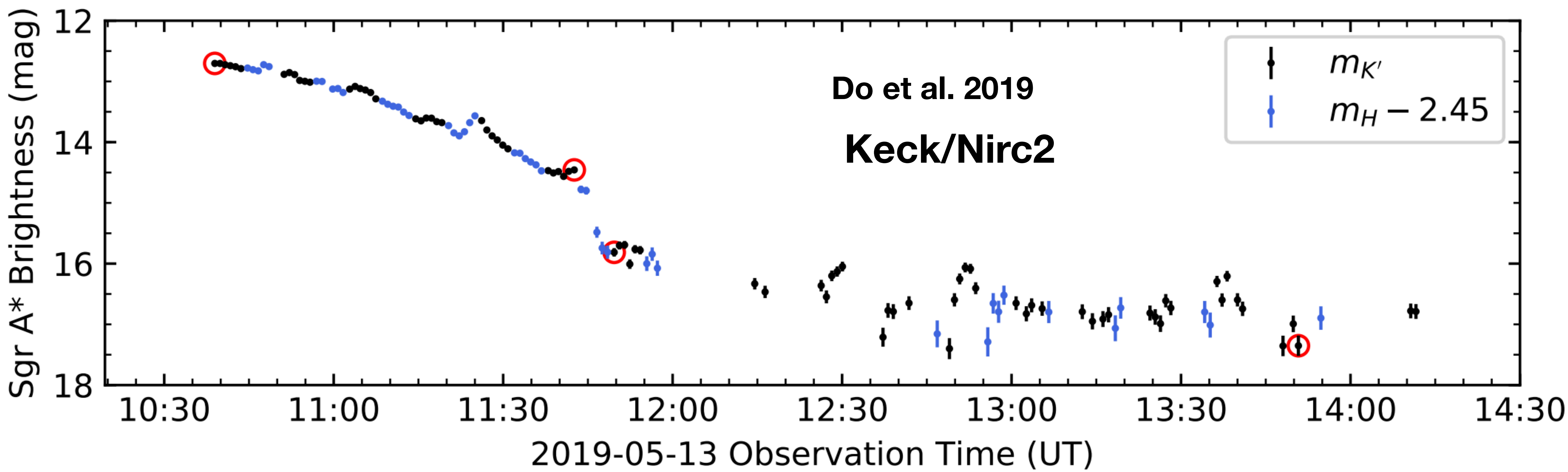
Witzel et al. 2018

Witzel et al. 2018



NIR Brightness record 2019

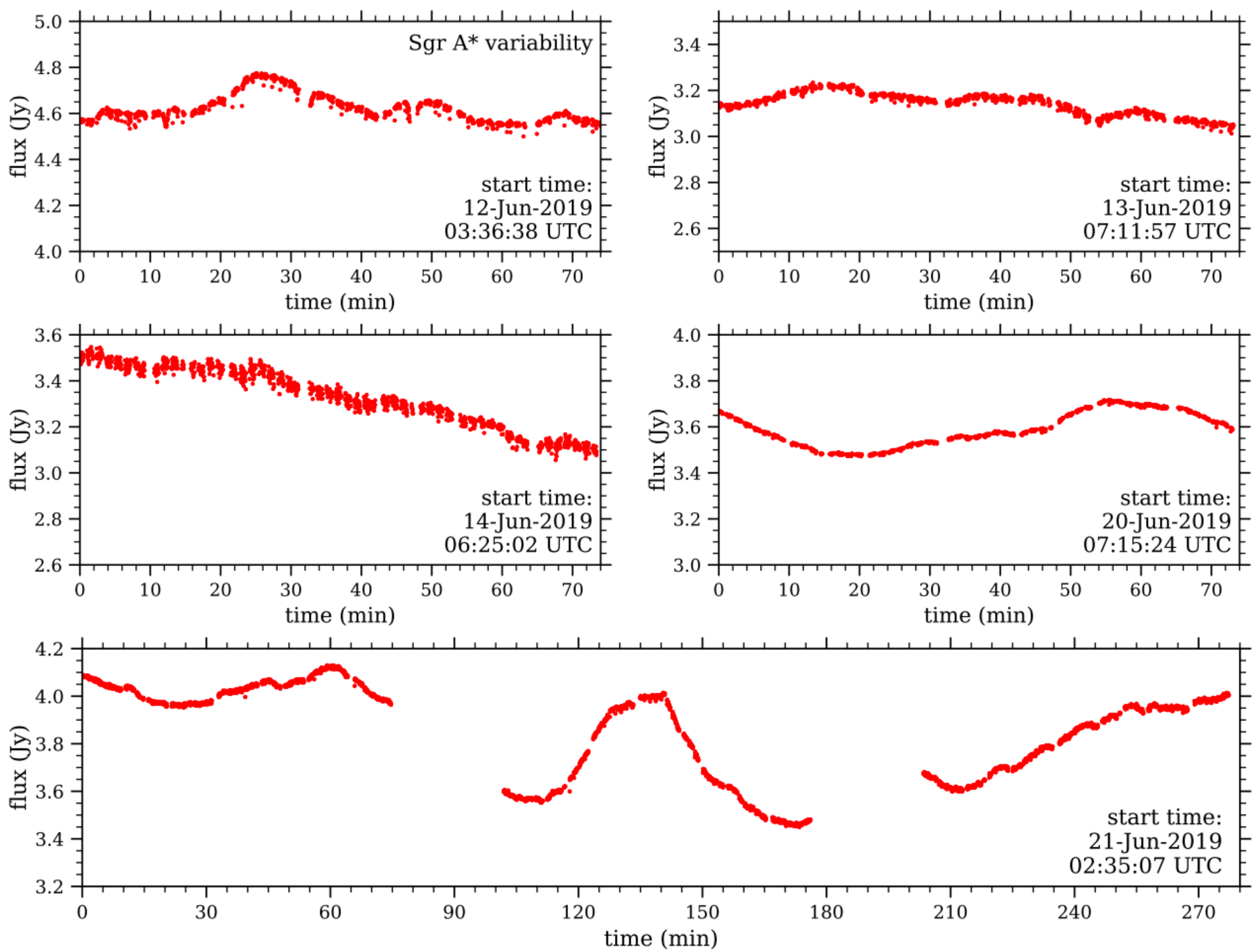


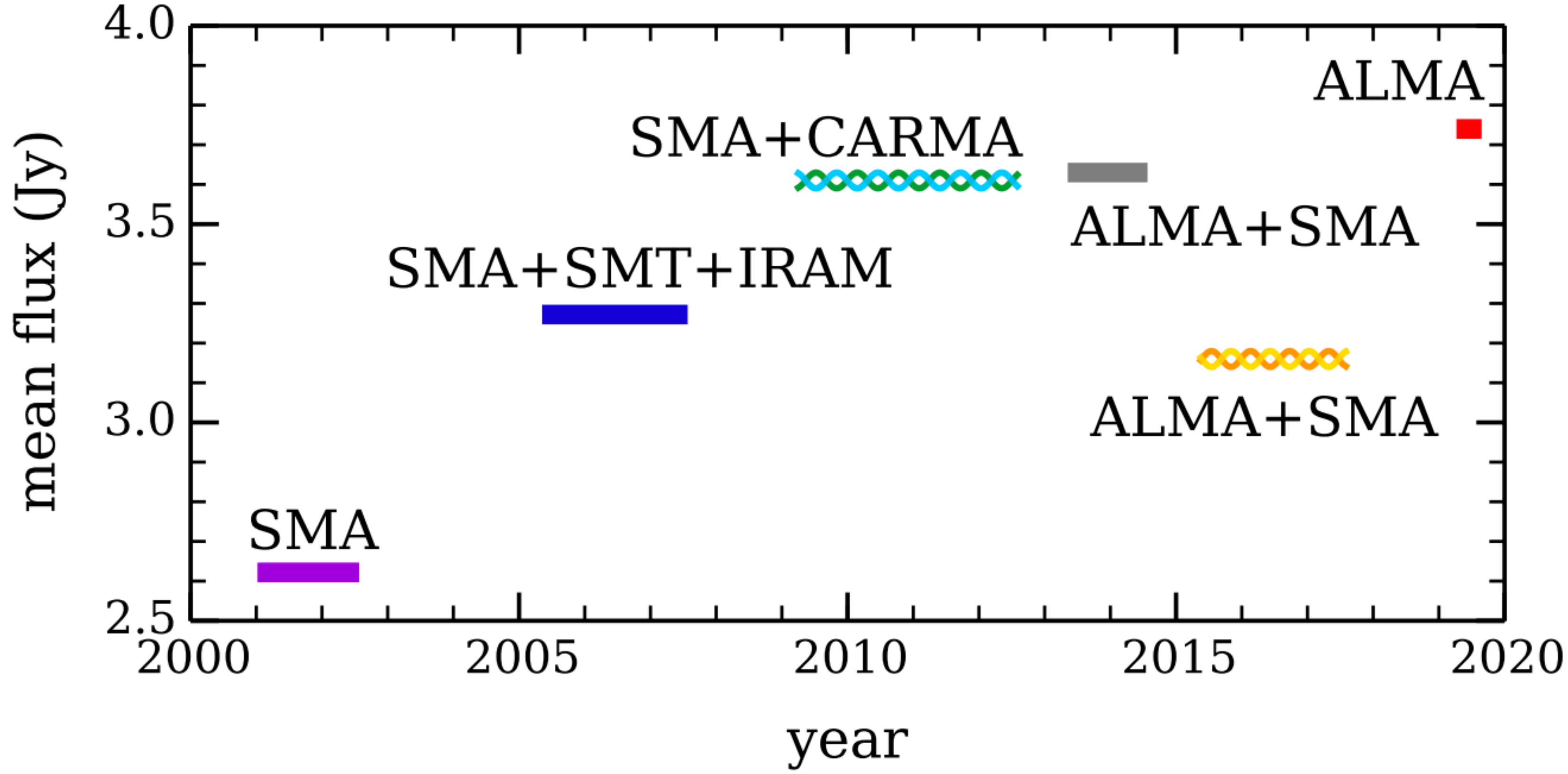


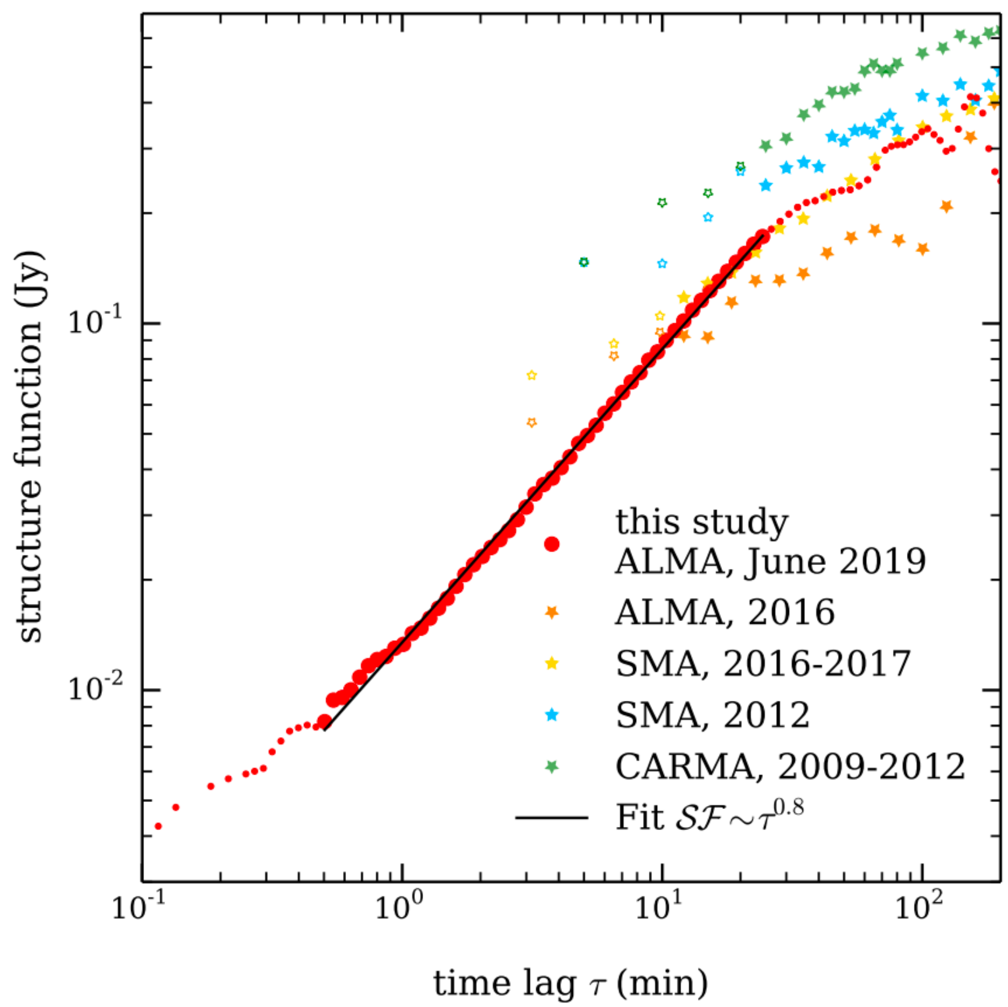
Second Scale Submillimeter Variability of Sagittarius A* during flaring activity of 2019: On the Origin of Bright Near Infrared Flares

Lena Murchikova[1] and Gunther Witzel[2]

[1]Institute for Advanced Study, 1 Einstein Drive, Princeton, NJ 08540, USA
[2]Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121, Bonn, Germany





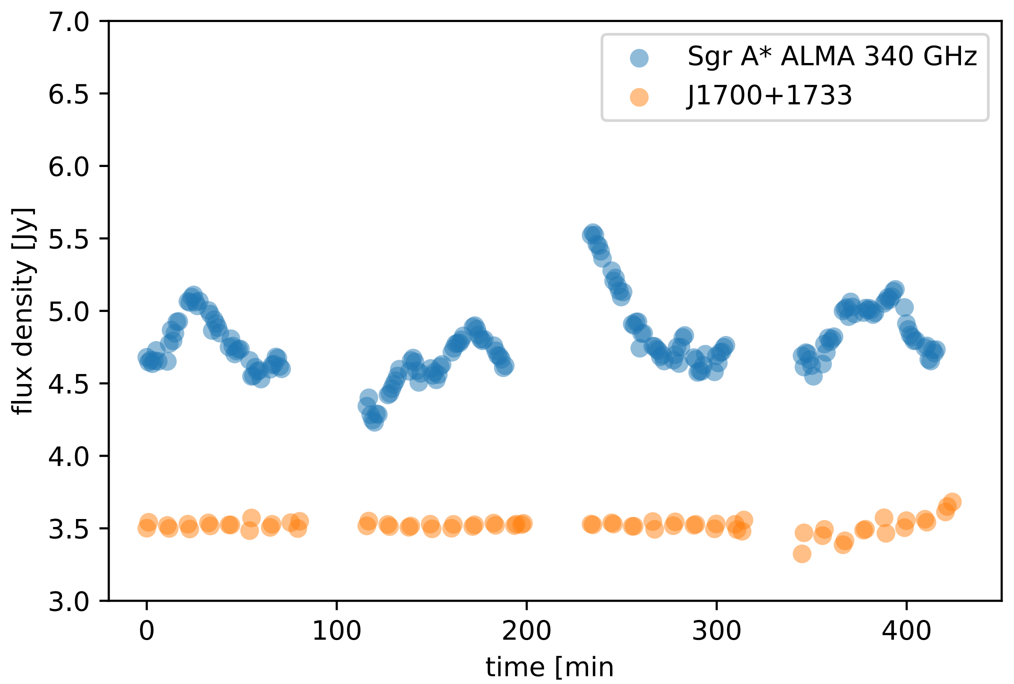


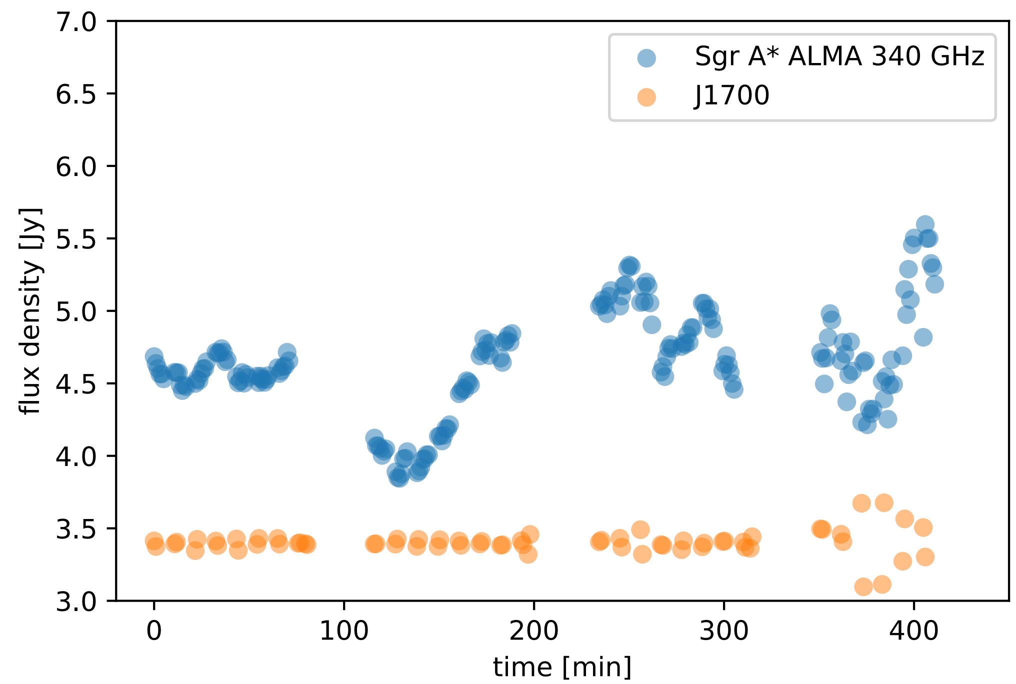
Murchikova & Witzel 2021

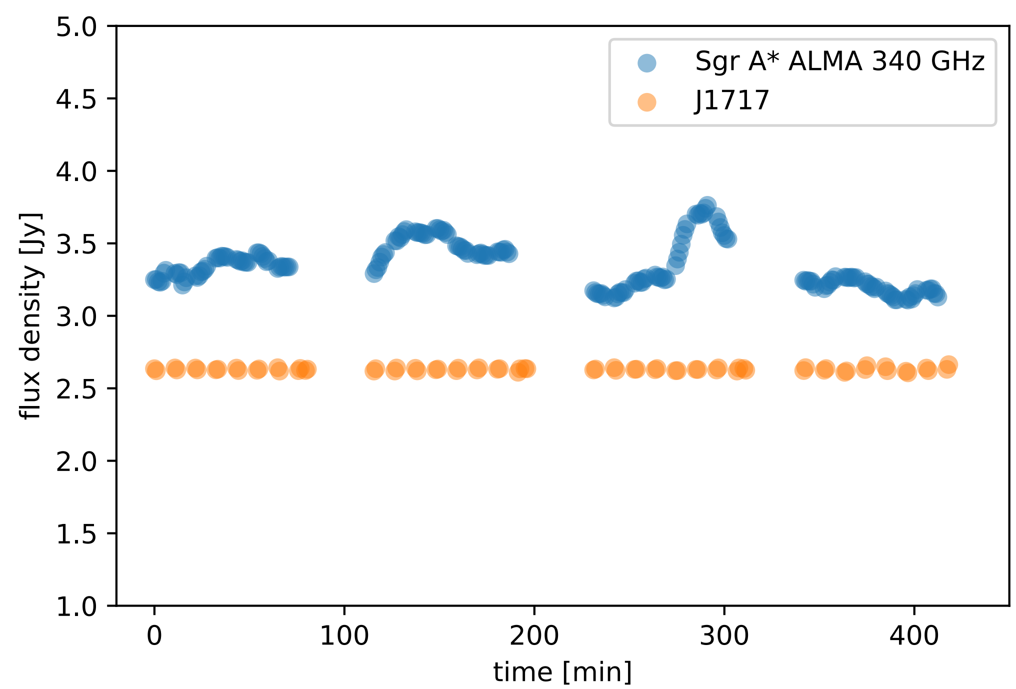
Other ALMA data in 2019

- **Submm/mm variability: is there long-term variability at work that we have not yet characterized?**

2019







Boyce et al. 2022 (accepted)

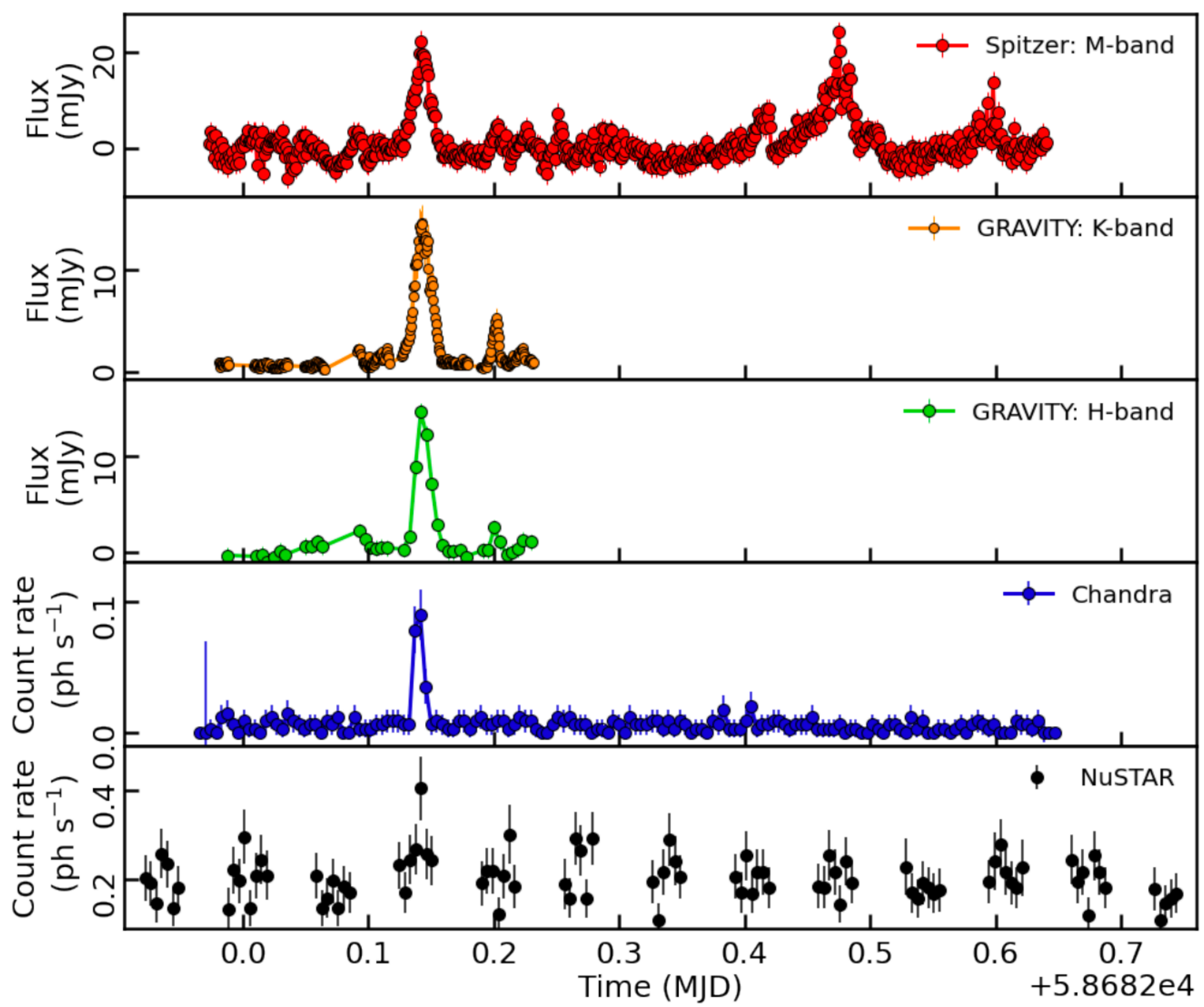
Constraining particle acceleration in Sgr A⋆ with simultaneous GRAVITY, *Spitzer*, *NuSTAR* and *Chandra* observations

GRAVITY Collaboration⋆: R. Abuter[8], A. Amorim[6,12], M. Bauböck[1], F. Baganoff[20], J.P. Berger[5,8], H. Boyce[21,22], H. Bonnet[8], W. Brandner[3], Y. Clénet[2], R. Davies[1], P.T. de Zeeuw[10,1], J. Dexter[14,1], Y. Dallilar[1], A. Drescher[1,17], A. Eckart[4,18], F. Eisenhauer[1], G.G. Fazio[19], N.M. Förster Schreiber[1], K. Foster[33], C. Gammie[25], P. Garcia[7,12], F. Gao[1], E. Gendron[2], R. Genzel[1,11], G. Ghisellini[13], S. Gillessen[1], M.A. Gurwell[19], M. Habibi[1], D. Haggard[21,22], C. Hailey[29], F. A. Harrison[33], X. Haubois[9], G. Heissel[2], T. Henning[3], S. Hippler[3], J.L. Hora[19], M. Horrobin[4], A. Jiménez-Rosales[1], L. Jochum[9], L. Jocou[5], A. Kaufer[9], P. Kervella[2], S. Lacour[2], V. Lapeyrère[2], J.-B. Le Bouquin[5], P. Léna[2], P.J. Lowrance[23], D. Lutz[1], S. Markoff[28], K. Mori[29], M.R. Morris[24], J. Neilsen[32], M. Nowak[16,2], T. Ott[1], T. Paumard[2], K. Perraut[5], G. Perrin[2], G. Ponti[14,1], O. Pfuhl[8,1], S. Rabien[1], G. Rodríguez-Coira[2], J. Shangguan[1], T. Shimizu[1], S. Scheithauer[3], H.A. Smith[19], J. Stadler[1], D. K. Stern[34], O. Straub[1], C. Straubmeier[4], E. Sturm[1], L.J. Tacconi[1], F. Vincent[2], S. von Fellenberg[1], I. Waisberg[15,1], F. Widmann[1], E. Wieprecht[1], E. Wiezorrek[1], S.P. Willner[19], G. Witzel[18], J. Woillez[8], S. Yazici[1,4], A. Young[1], S. Zhang[30], and G. Zins[9]

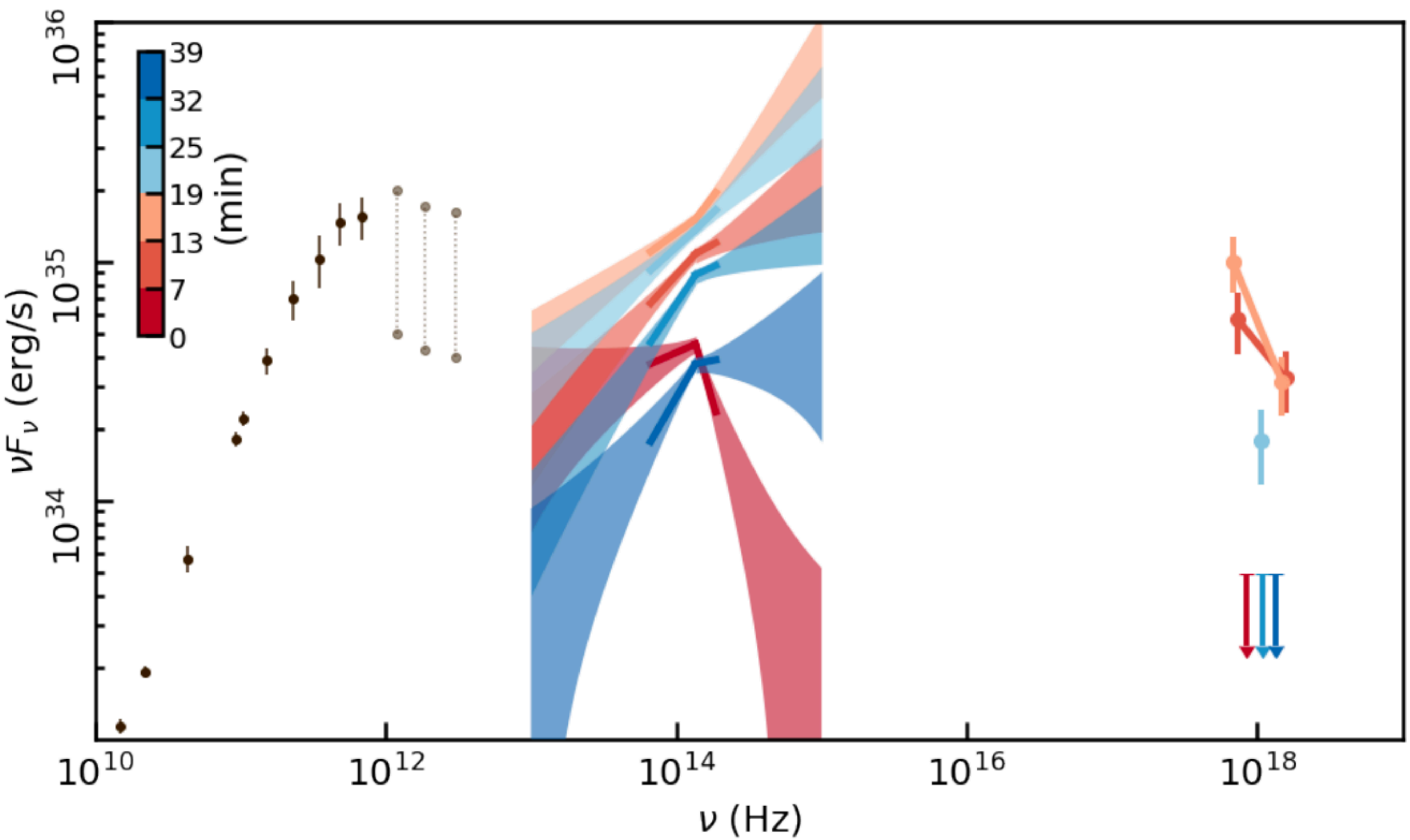
(Affiliations can be found after the references)

2 Jul 2021

Received July 5, 2021; accepted future

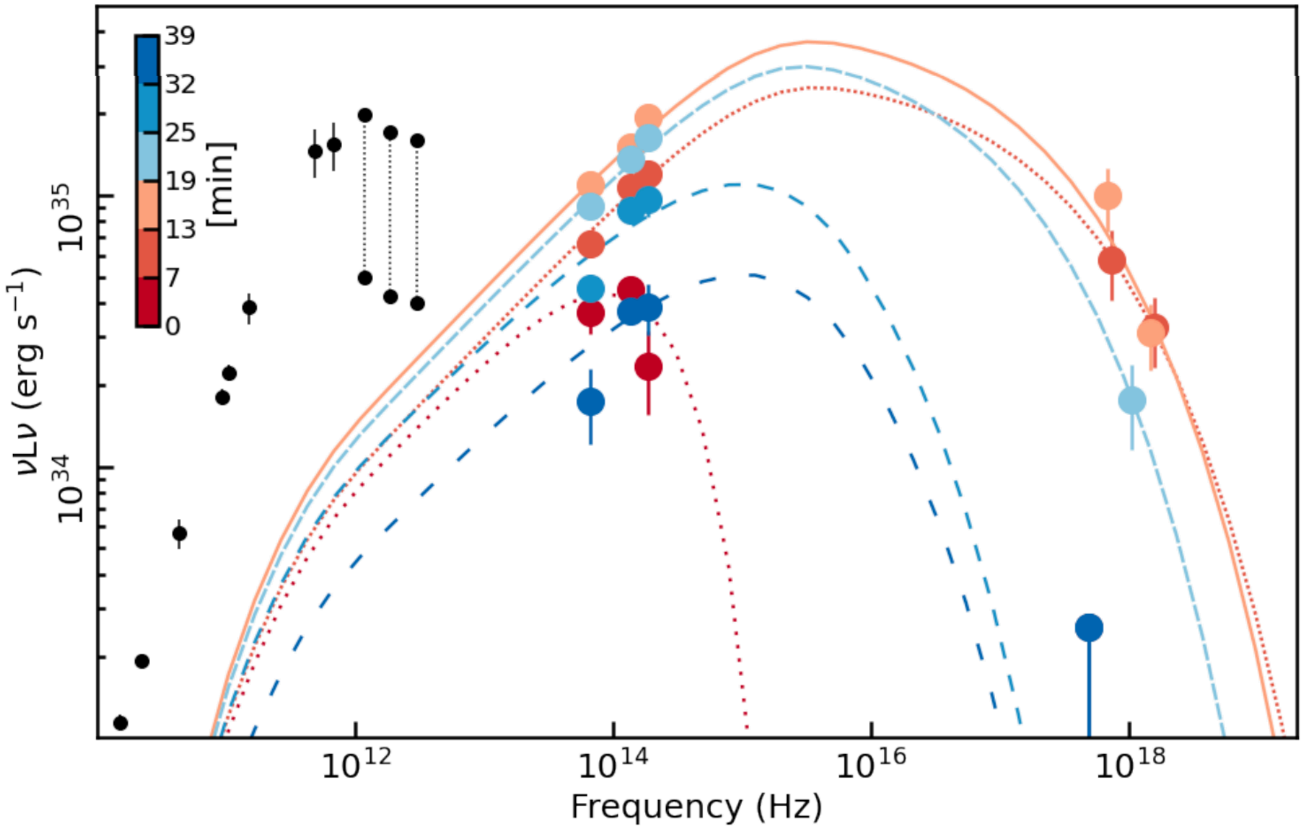


Real time SED measurement with Spitzer, Gravity, Chandra, and NuStar



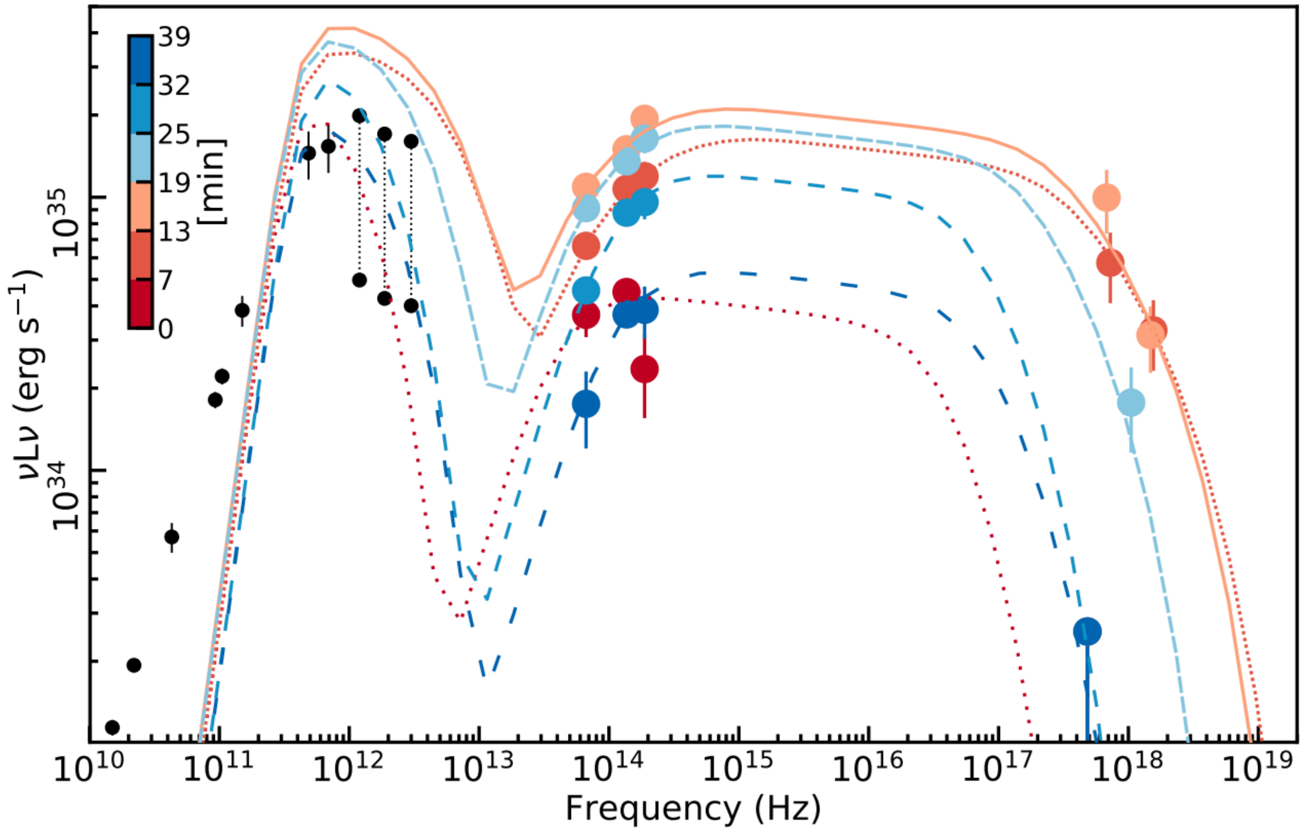
Two family of models

Sync-Sync



High electron energies

Sync-SSC



High electron densities

Multi-wavelength Observations of Sgr A* – I. 18 July 2019

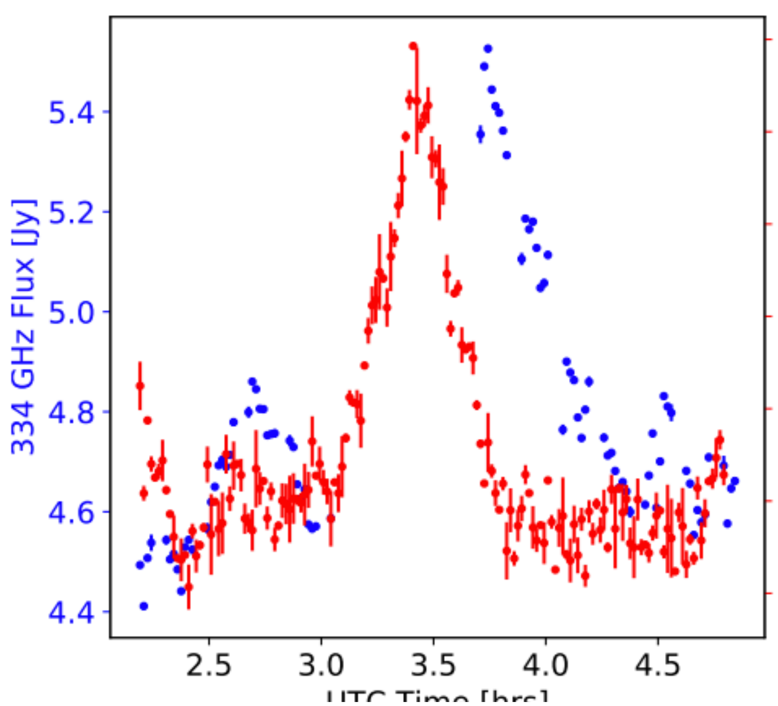
Joseph M. Michail[1], Mark Wardle[2], Farhad Yusef-Zadeh[1] and Devaky Kunneriath[3]

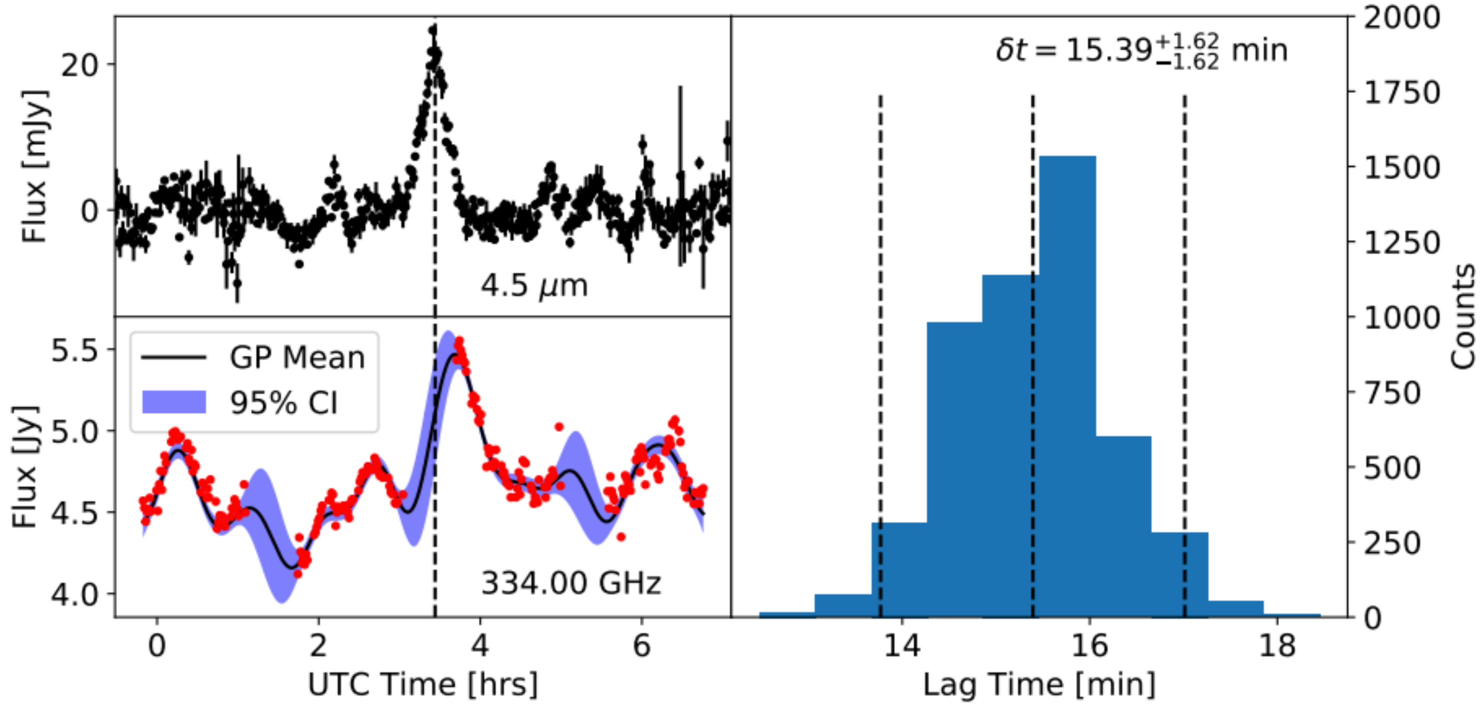
[1] Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) and Department of Physics and Astronomy, Northwestern University, 1800 Sherman Ave., Evanston, IL 60201, USA

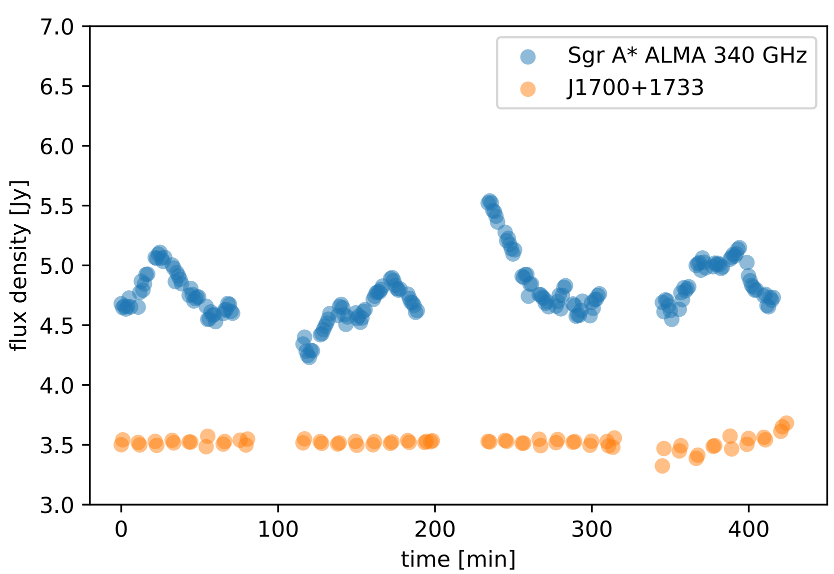
[2] Research Centre for Astronomy, Astrophysics and Astrophotonics and Department of Physics and Astronomy, Macquarie University, Sydney, NSW 2109, Australia

[3] National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA

Spitzer + ALMA

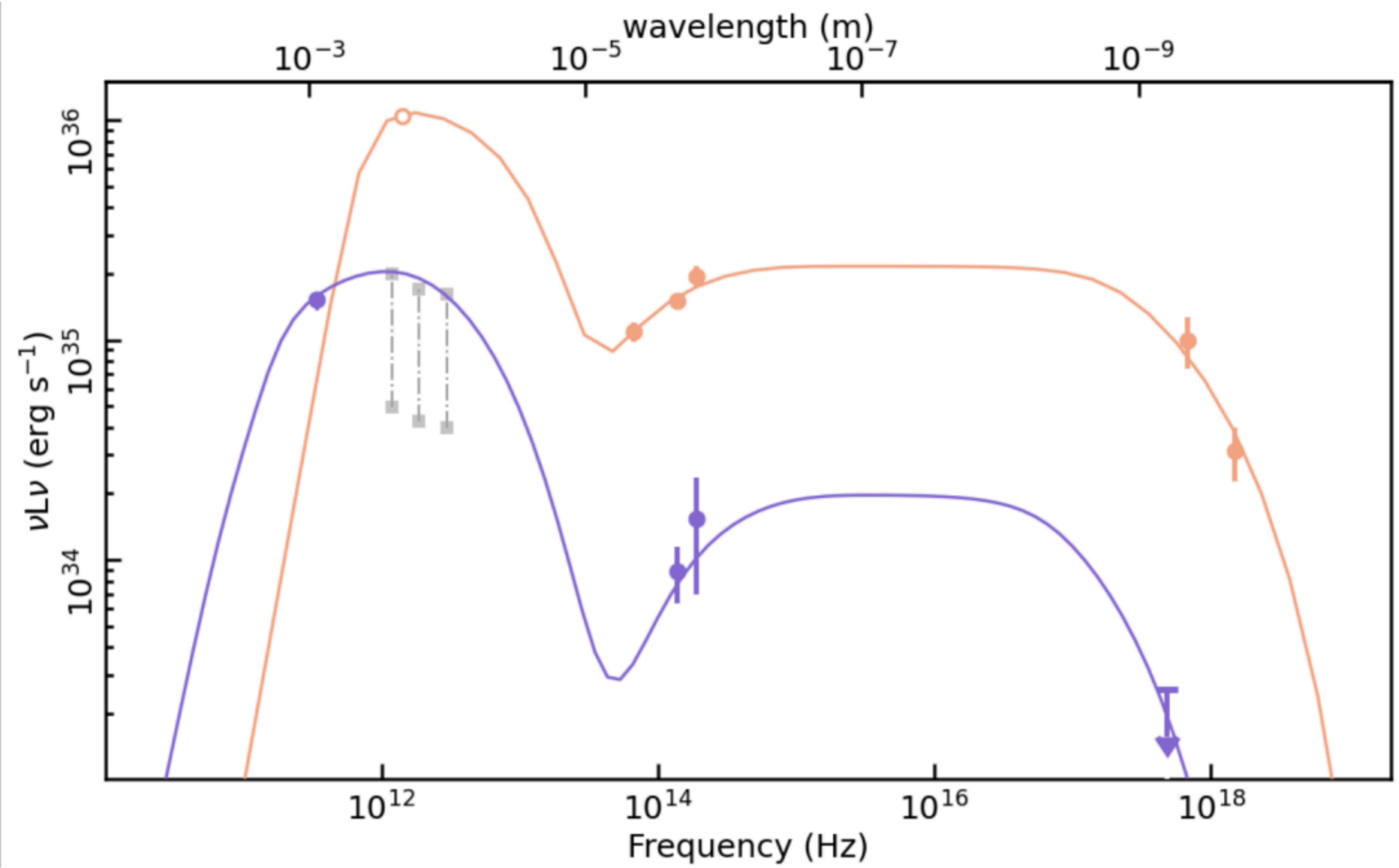




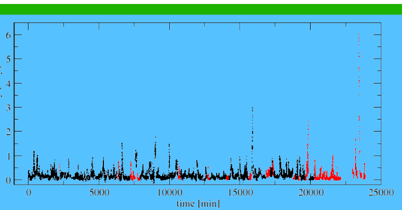


Boyce et al. 2022 (accepted)

Adiabatic expansion works



Boyce et al. 2022 (accepted)




Outlook

NIR-MIR SED: does the synchrotron spectrum cut off in the NIR? Is SSC contributing at times?

Credit: Northrop Grumman

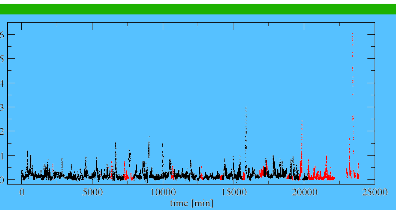
Outlook

GRAVITY

?

EHT

?




Thank you!