

How a Black Hole Feeds: Multi-wavelength Observations of Sgr A*

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Sgr A* - Black Hole at the GC

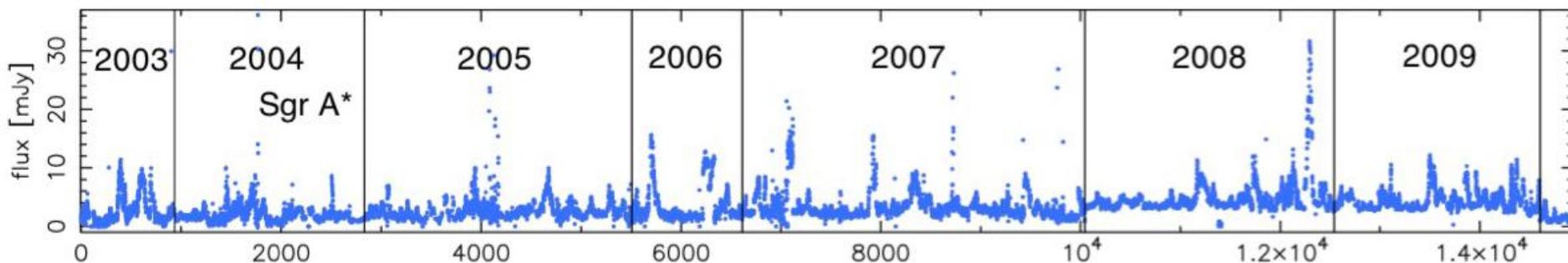
- Very “under-luminous”: 10^{-9} of Eddington luminosity for a $\sim 4 \cdot 10^6 M_{\odot}$ object.
- Flare-like emission seen from the accretion flow onto Sgr A* in the radio, submm, NIR (1.6 – 4.5 μm), and X-ray.
- Emission is variable at all of these wavelengths.
- Timescale of variability indicates it is emitted near innermost stable orbit of the black hole.

Sgr A* Variability

- **X-rays (Chandra, XMM, Swift, NuStar)**
 - Observed from 2 – 79 keV, $\sim 1/\text{day}$
 - Rapid in duration (~ 0.5 hr), although 3 hr flares have been observed.
 - Substantial substructure within a flare (~ 100 sec) indicating flare comes from very compact regions (~ 10 Schwarzschild radii).
 - Quiescent flux extended and extremely faint
 - Amplitude of flares few tens to ~ 160 times quiescent flux.

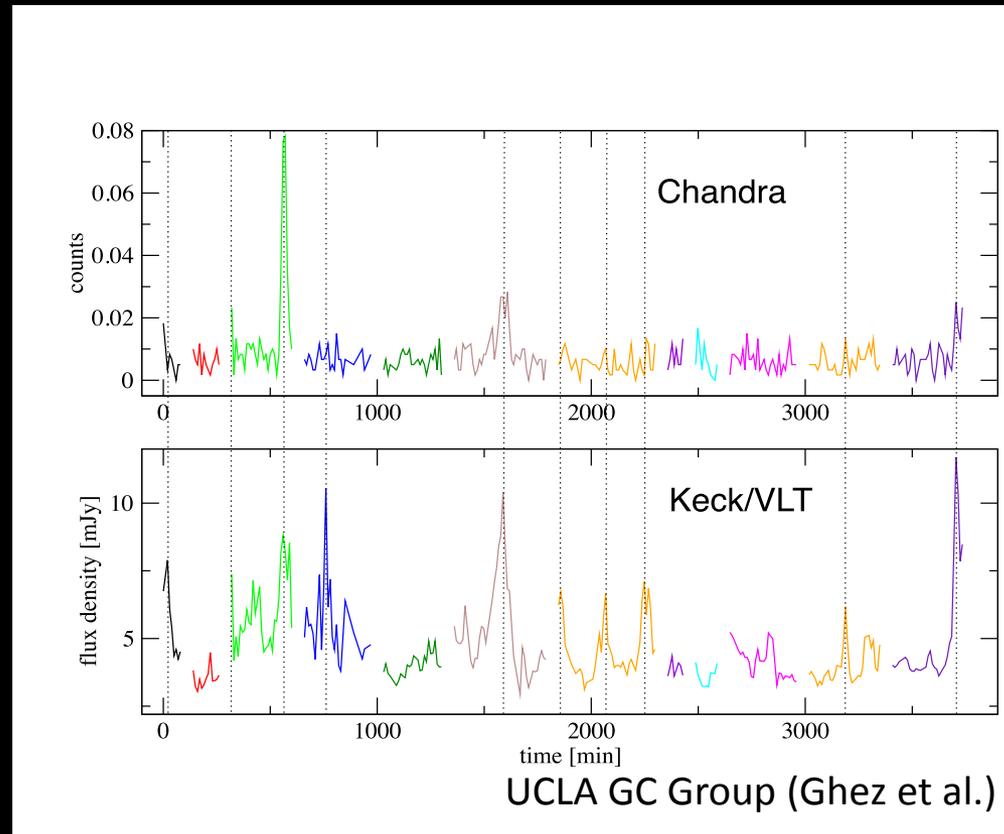
Sgr A* Variability

- **Near-Infrared (1.6 – 4.5 μm ; VLT, Keck, Spitzer)**
 - No evidence of a quiescent state
 - Continuously variable flux; 4 – 5 flares/day
 - Flare duration ~ 0.5 to 2 hrs
 - Substantial substructure: timescale ~ 47 sec
 - Peak amplitude ~ 30 mJy; noise amplitude ~ 1 mJy
 - Emission strongly polarized, suggesting synchrotron emission
 - Power law spectrum ($S \sim \lambda^\alpha$; $\alpha \sim 0.6$); radiation optically thin synchrotron emission from power-law electrons



NIR (K band) - X-ray Correlation

- *Chandra* X-ray flares have corresponding NIR peaks
- Some bright NIR peaks have no X-ray flare
- No clear correlation between X-ray and NIR brightness
- One *XMM* flare observed with no or very weak NIR peak

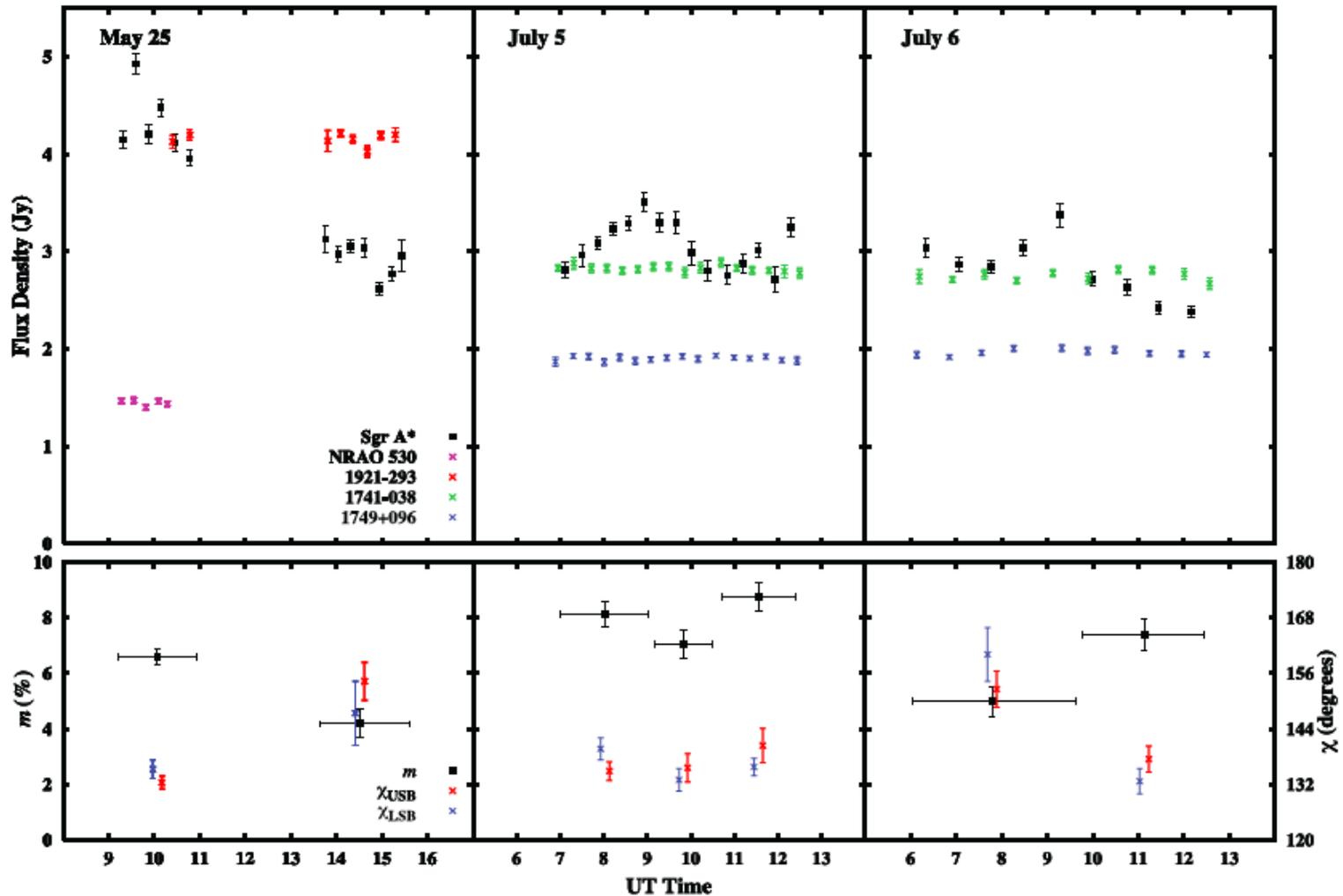


Sgr A* Variability

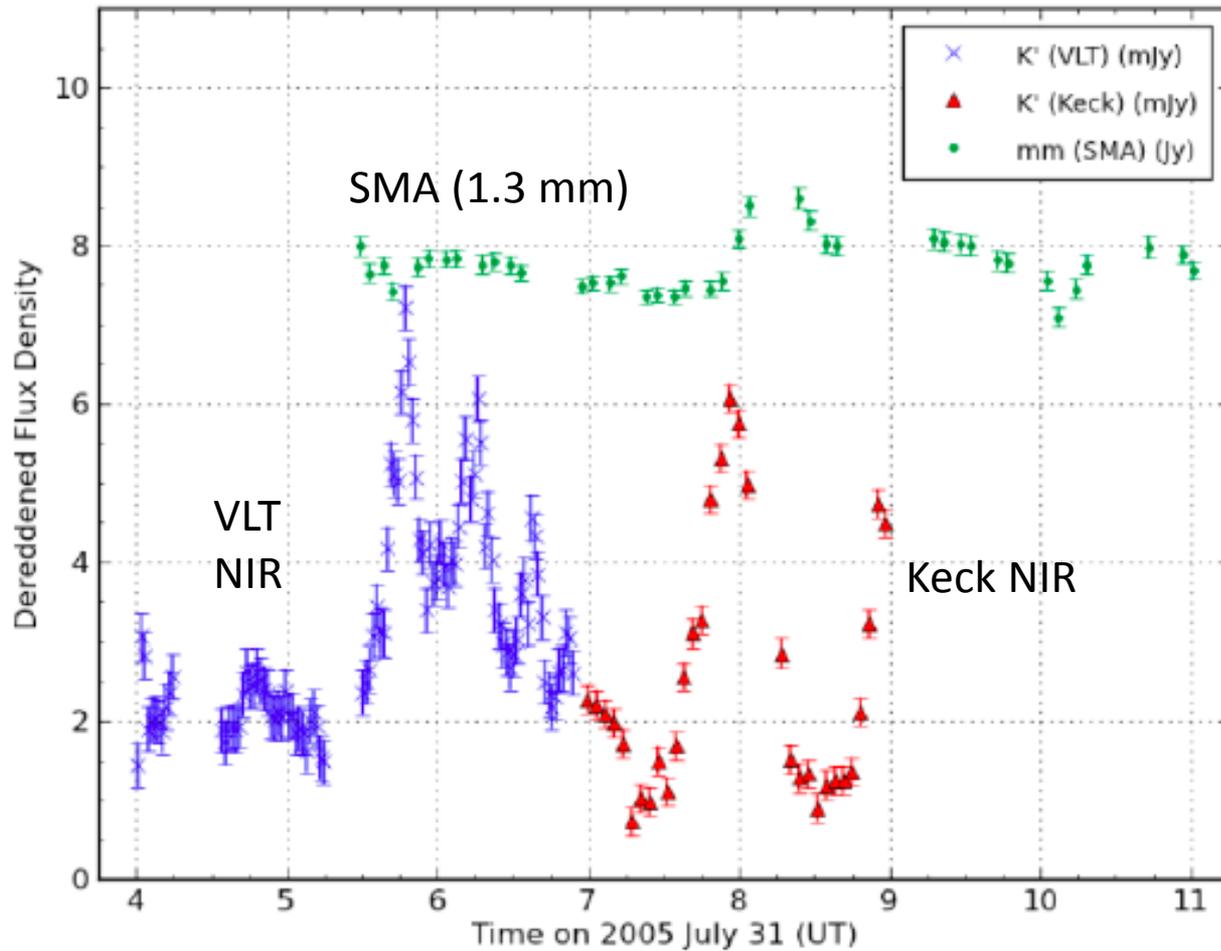
- **Millimeter/Submillimeter (SMA, APEX, CSO)**
 - Observed from 450 μm to 1.3 mm
 - Relatively constant emission (~ 3 Jy at 850 μm and ~ 3.5 Jy at 1.3 mm)
 - SED peaks in submm, consistent with synchrotron emission from thermal electrons near innermost stable orbit of BH
 - Flaring events on time scales of hours to days, with 25% outbursts once per day
 - Linear polarizaiton has also been observed in submm flare emission, increasing from 9% to 17% as the flare passes through peak emission

Sgr A* Variability

Submm Intensity and Polarization



Sgr A* NIR/Submm Light Curves



Sgr A* Light Curve

NIR/submm time lags

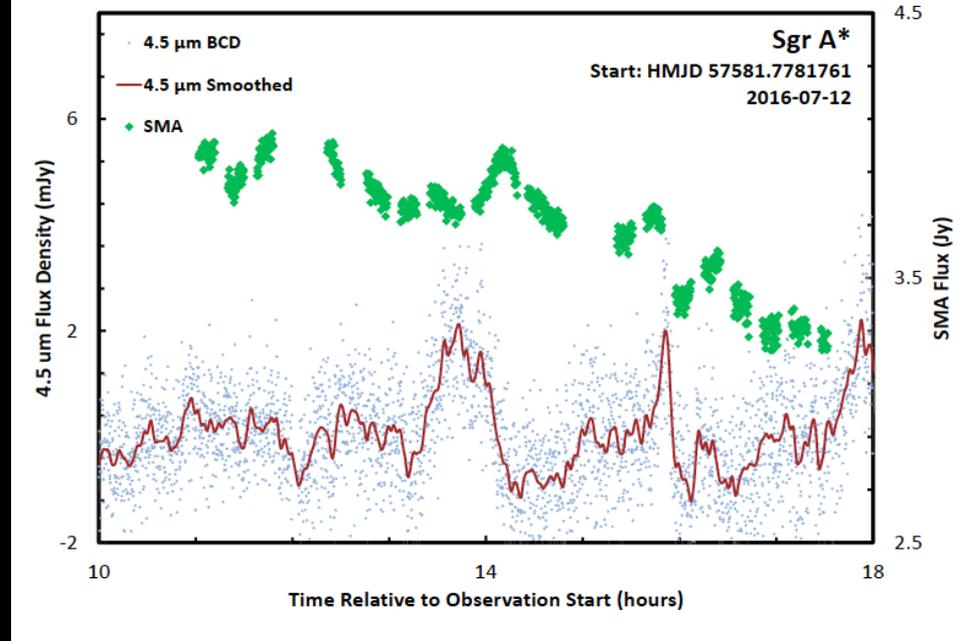
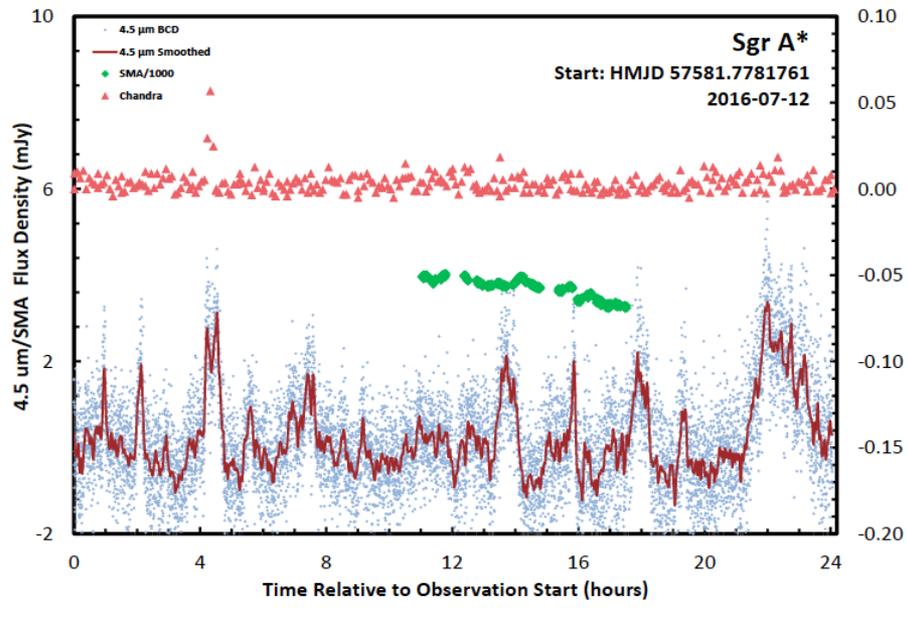
Table 1 Reported time lags between near-infrared and millimeter/submillimeter peaks in the Sgr A* light curve.

References	Date	Wavelength (μm)	Time Lag (min)
[1, 2]	2004 Jul. 7	890	< 120
[3]	2004 Sep. 3	850	160
[4,5,6]	2006 Jul. 17	1300, 850	100
[6]	2007 Apr. 5	1300	160
[7]	2008 Jun. 3	870	90
[8]	2009 Apr. 1	870	200
[4]	2005 Jul. 31	1300	20
[9]	2005 Jul. 31	1300	160

References: [1] Eckart et al. (2006a), [2] Eckart et al. (2009), [3] Yusef-Zadeh et al. (2006a), [4] Marrone et al. (2008), [5] Yusef-Zadeh et al. (2008), [6] Yusef-Zadeh et al. (2009), [7] Eckart et al. (2008), [8] Trap et al. (2011), [9] this work.

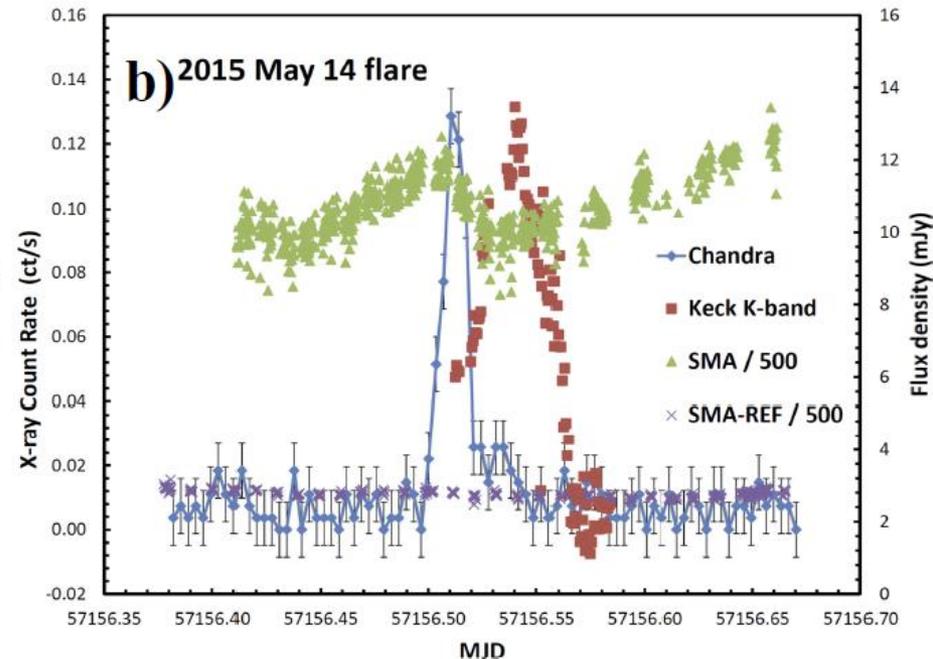
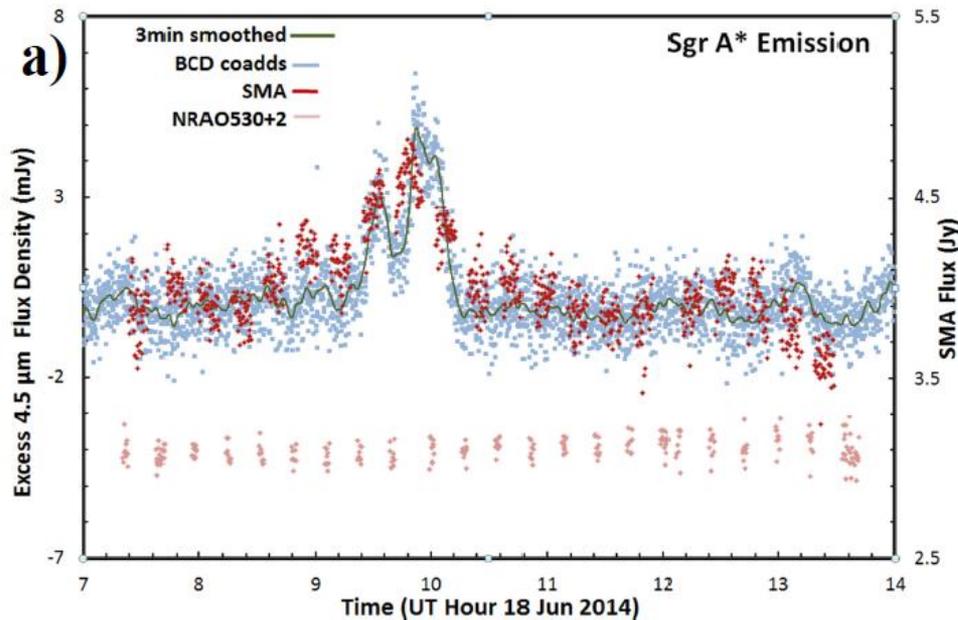
Sgr A* Variability

July 12, 2016



Submm Flare Sequence

- Previously, X-ray and IR flares coincident, sub-mm flare follows
- Recent observations contradict both “rules”
- Need more observations to sample all types of flares, might be several mechanisms



Sgr A* Variability Models

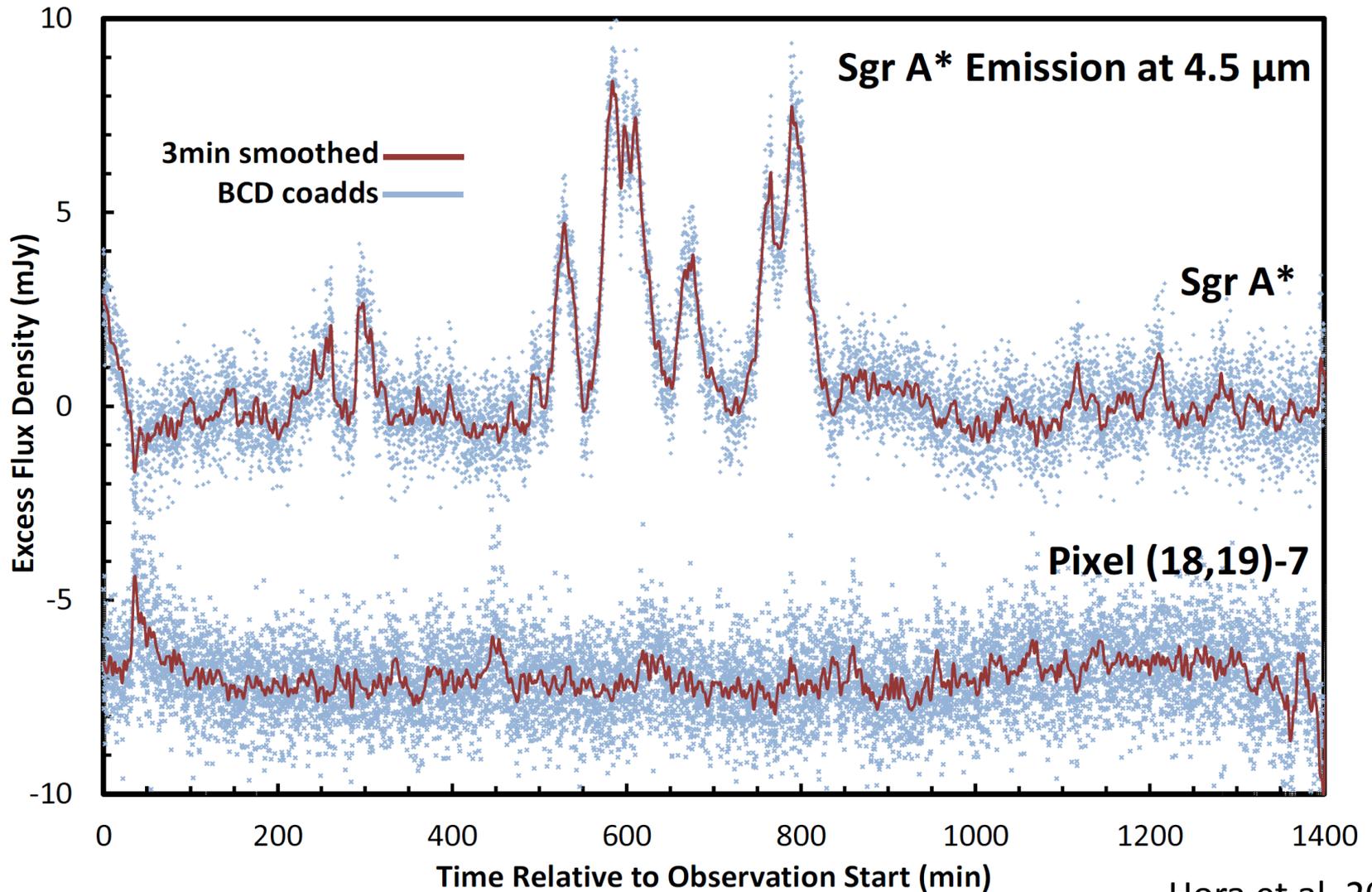
- Emission mechanisms of the variability are still not understood. Possibilities are:
 - magnetic reconnection events or shocks in an inhomogeneous accretion flow
 - adiabatically expanding plasma blobs
 - intermittent jets or unstable jet shocks
 - multiple orbiting and evolving hot spots
 - stochastic acceleration in the inner accretion flow
 - tidal disruption of infalling asteroids
- While the NIR and submm are identified to arise from synchrotron emission, the origin of the X-ray emission is still unknown. Possibilities for the X-ray process are:
 - synchrotron with a cooling break
 - synchrotron self-Compton and external Compton scattering of submm seed photons off NIR emitting electrons and/or NIR photons off of submm-emitting electrons
- Theoretical program [CfA (R. Narayan, E.Keto); Illinois (C. Gammie)]

Sgr A* Variability Multi-wavelength Program

Key feature – important to observe simultaneously in long continuous periods in IR, X-ray, submm

- **2013 December** – 24hr Spitzer
- **2014 June-July** – 3 x 24hr Spitzer, limited overlap with SMA, Chandra
- **2016 July** – 2 x 24hr Spitzer/Chandra epochs
 - Submm (SMA, ALMA), VLA, Near-IR (Keck, VLT), GTC, (EHT)
- **2017 July** – 2 x 24hr Spitzer/Chandra epochs
- **>2018** – JWST, SMA, ALMA, Keck, VLT, Chandra, ATHENA, EHT

Sgr A* Variability at 4.5 μm



December 2013 – July 2014

