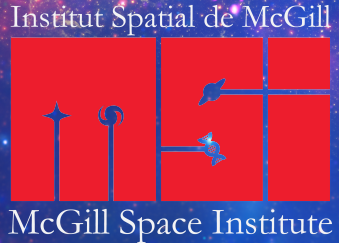
Black Holes Across the EM Spectrum

KISS Study Program 2019:

Beyond Interstellar - Extracting Science from Black Hole Images



Daryl Haggard
McGill University
Canada Research Chair

How do we connect horizon-scale findings with “the rest” of BH science?

What are the big/open questions?

Chat with your neighbor for 3-5 mins…

What are the big/open questions?

1. *How do contemporaneous EM observations of SMBH variability trend with horizon-scale variability (traced by EHT, GRAVITY, etc.)?*

- Will these trends for M87 and Sgr A* apply to populations of LLAGN?
- What about higher accretion rate systems?
- Stars vs. gas vs. photons as probes of the event horizon...
- Accretion!!!

What are the big/open questions?

2. *How do we use other probes of BH mass (stellar/gas dynamics, LIGO/Virgo, LISA, pulsar timing) with horizon scale measures to expand our understanding of BH astrophysics?*

- BH scaling relations
- BH and SMBH variability (AGN structure function, BH hysteresis, flares/flickering)
- BH spins ??

What are the big/open questions?

3. *Is the formation of primordial black holes a main driver for this science case (for future proposals, missions, etc.)?*

- Occupation fraction
- Formation and accretion theory

4. *What are the most important timescales and how do they connect?*

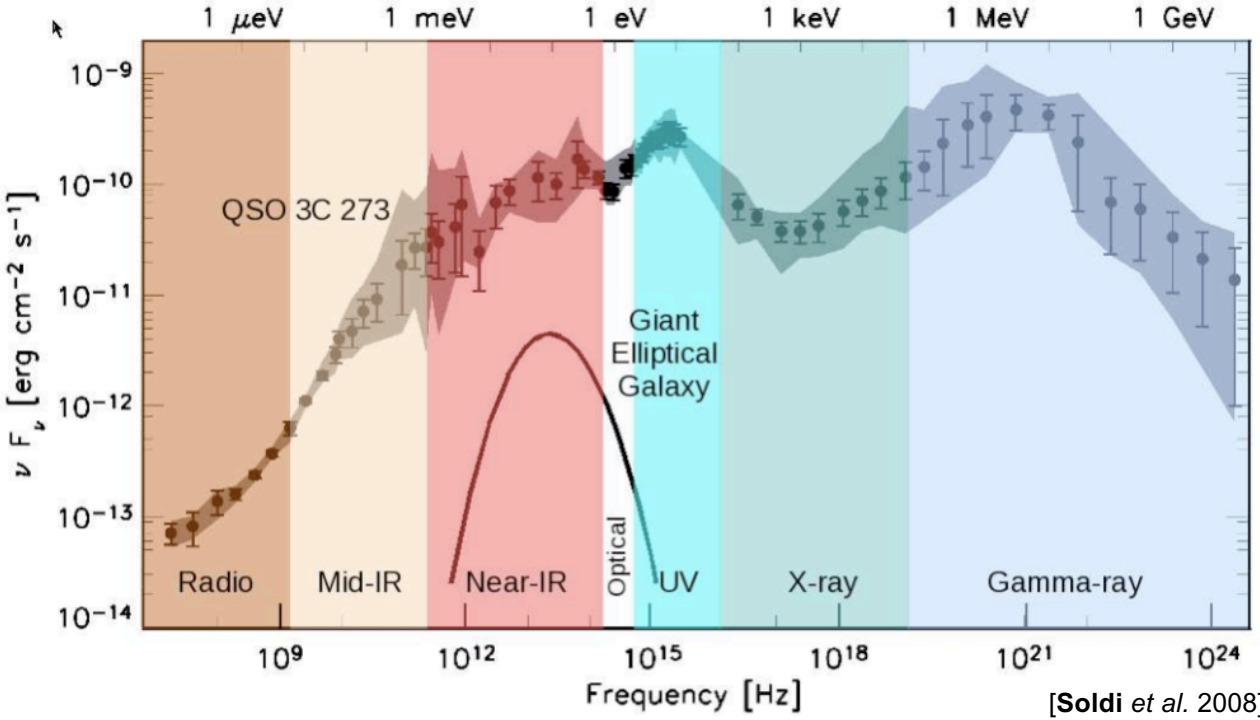
- formation time for small vs. large BH
- for SMBH is this really the "evolution timescale"
- time to grow mass vs. sink to center of gravitational potential

What are the big/open questions?

5. *How important is it that GW experiments rely on binaries, while other tracers (and trends) look at single systems?*

- Why don't we see an EM counterpart to LIGO BH mergers?
- What's the likelihood that of a GW source at the Galactic Center? One in M87?

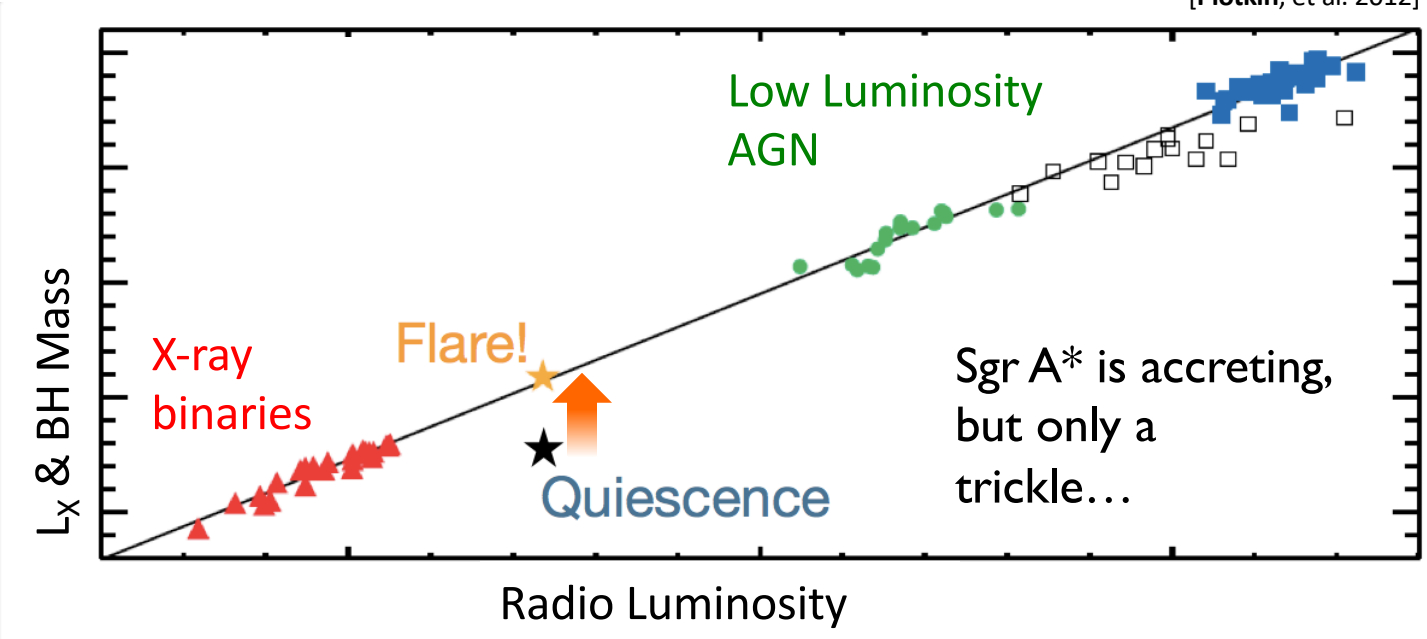
QSO/AGN Spectral Energy Distribution (SED)



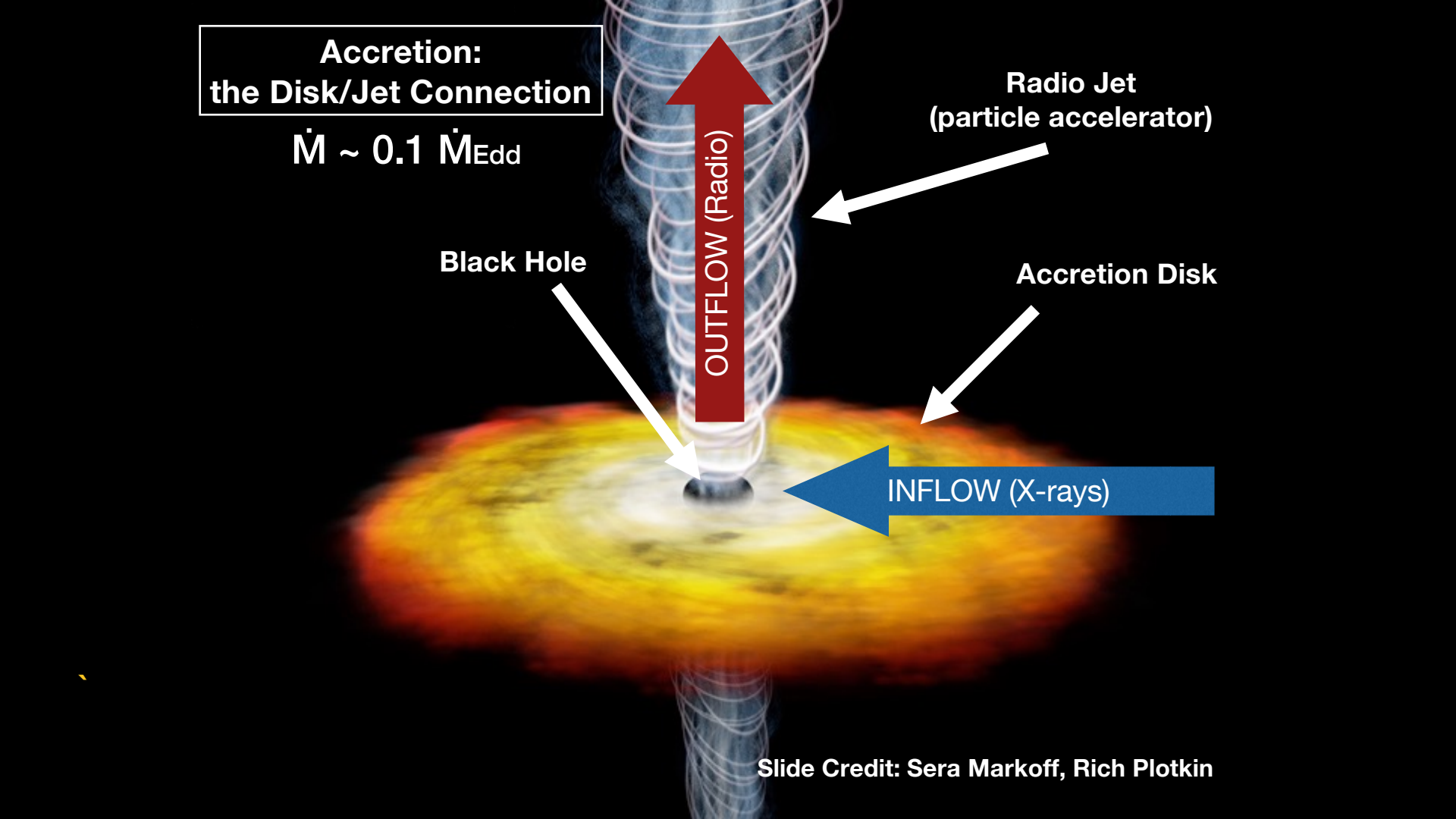
[**Soldi** *et al.* 2008]

Black Hole "Fundamental Plane"

[**Plotkin**, et al. 2012]

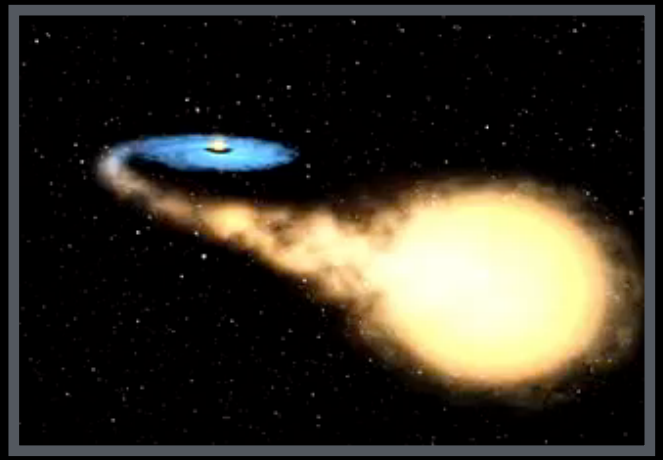


Does Sgr A* reside on the BH fundamental plane?


Accretion:
the Disk/Jet Connection
$\dot{M} \sim 0.1\ \dot{M}_{Edd}$
Radio Jet
(particle accelerator)
OUTFLOW (Radio)
Black Hole
Accretion Disk
INFLOW (X-rays)
Slide Credit: Sera Markoff, Rich Plotkin

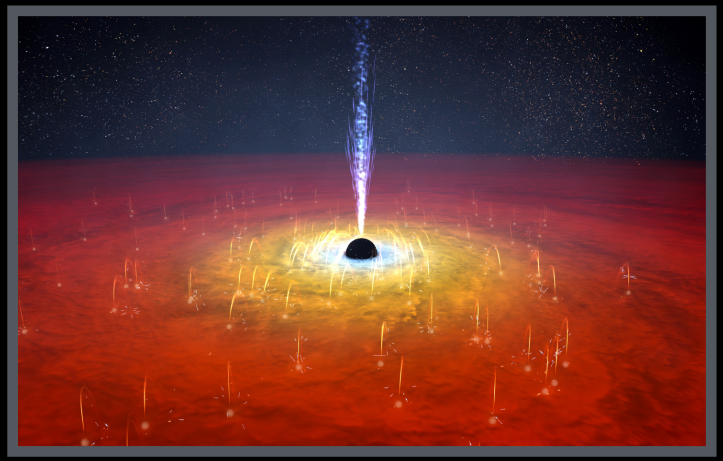
X-ray Binaries as Scale Models

X-ray Binaries
M_{BH} ~10 M_{Sun}



Credit: NASA/STSCI

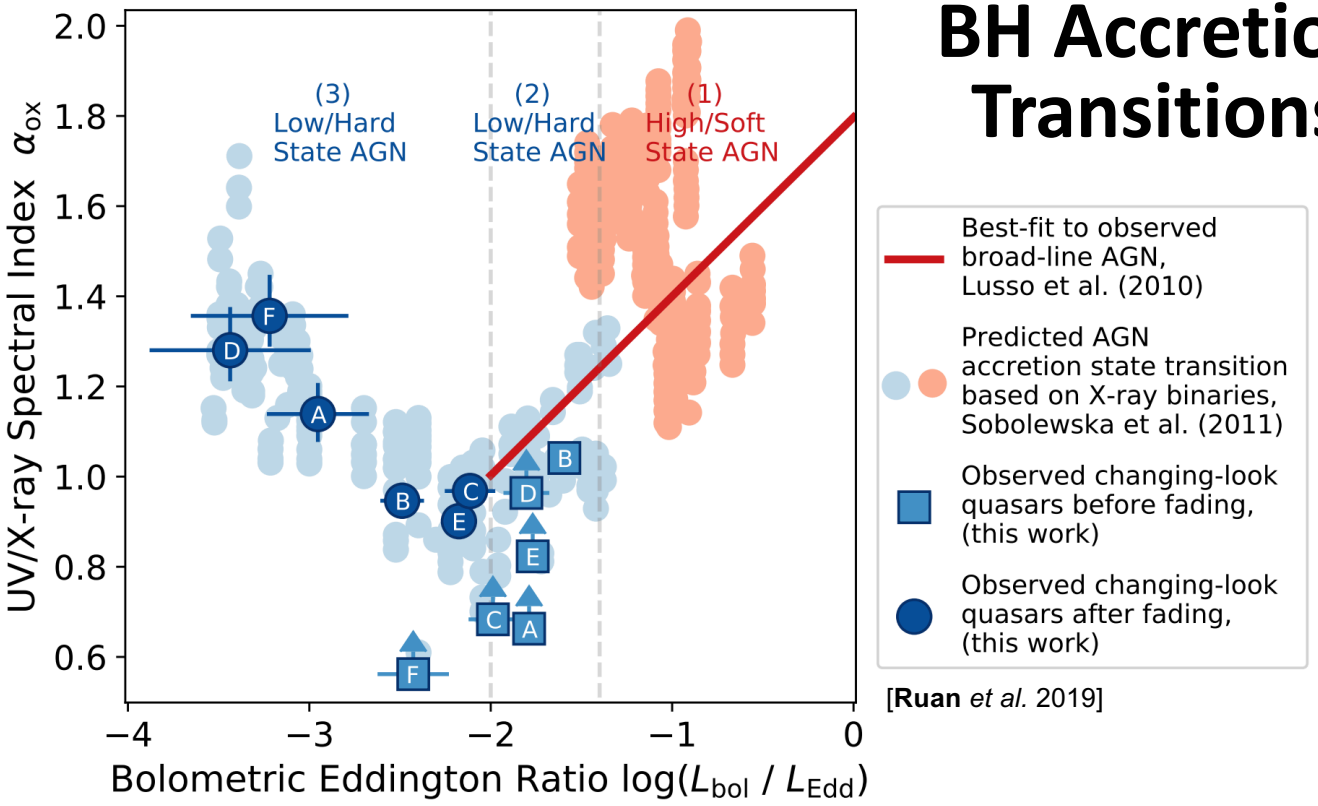
Active Galactic Nuclei
$M_{BH} \sim 10^6 - 10^9$ M_{Sun}



Credit: Tr'Ehnl & Brandt (2017)

Slide Credit: Rich Plotkin

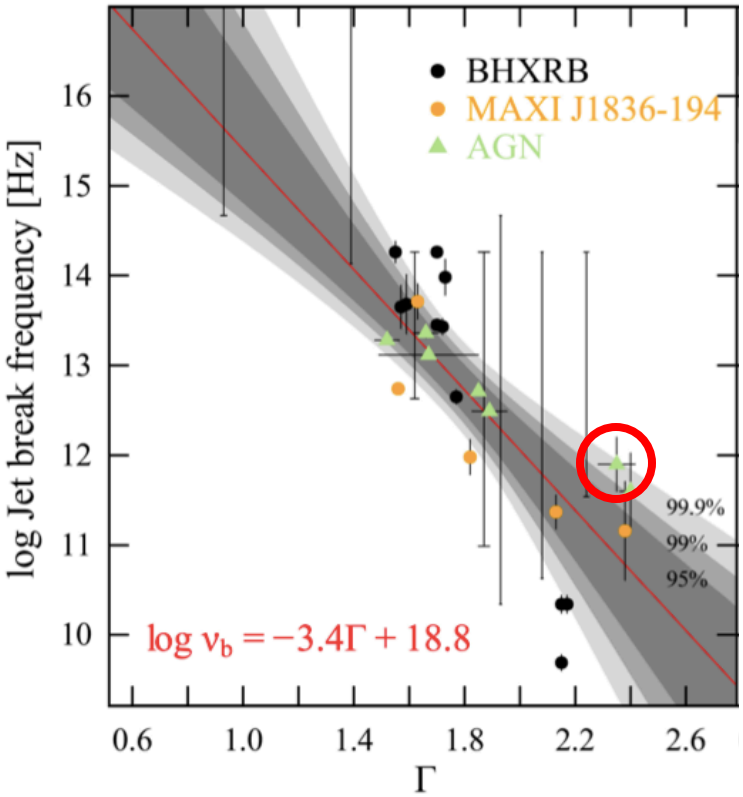
BH Accretion Transitions



[**Ruan** *et al.* 2019]

Plasma Conditions & Jets

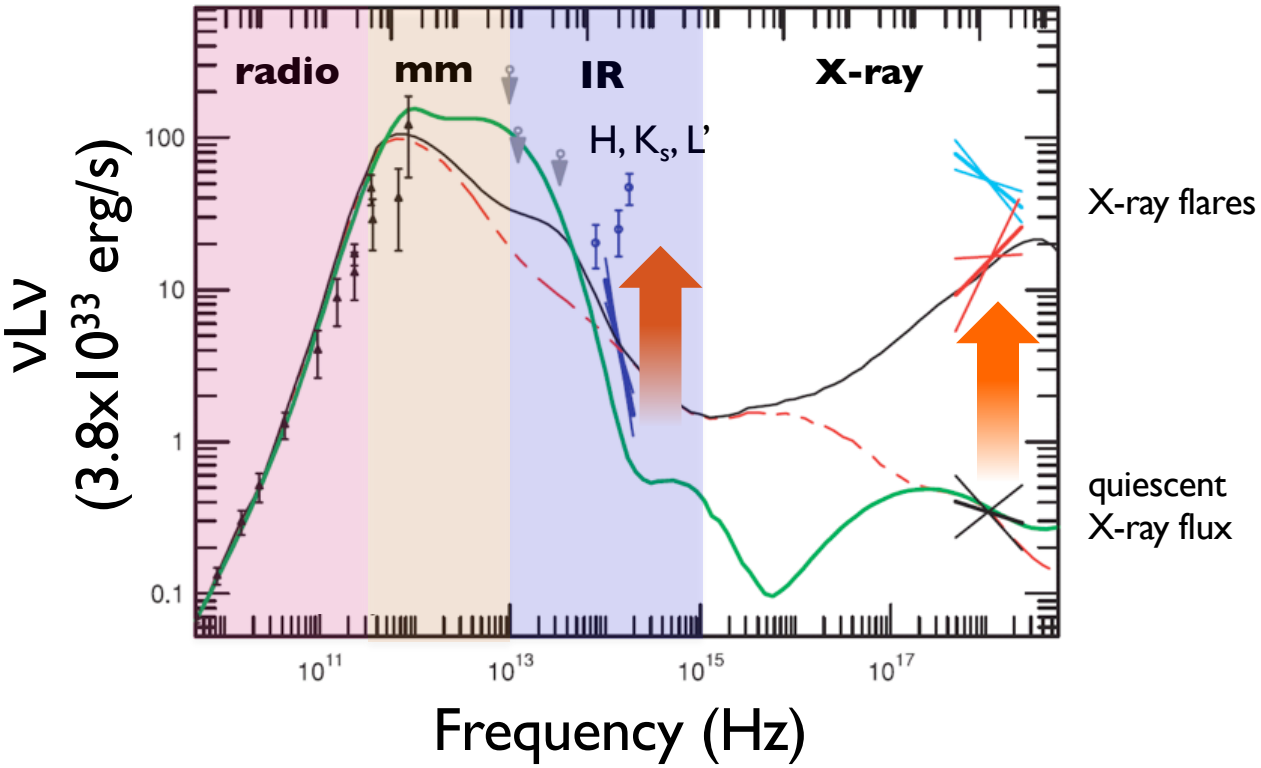
[**Koljonen**, et al. 2015]



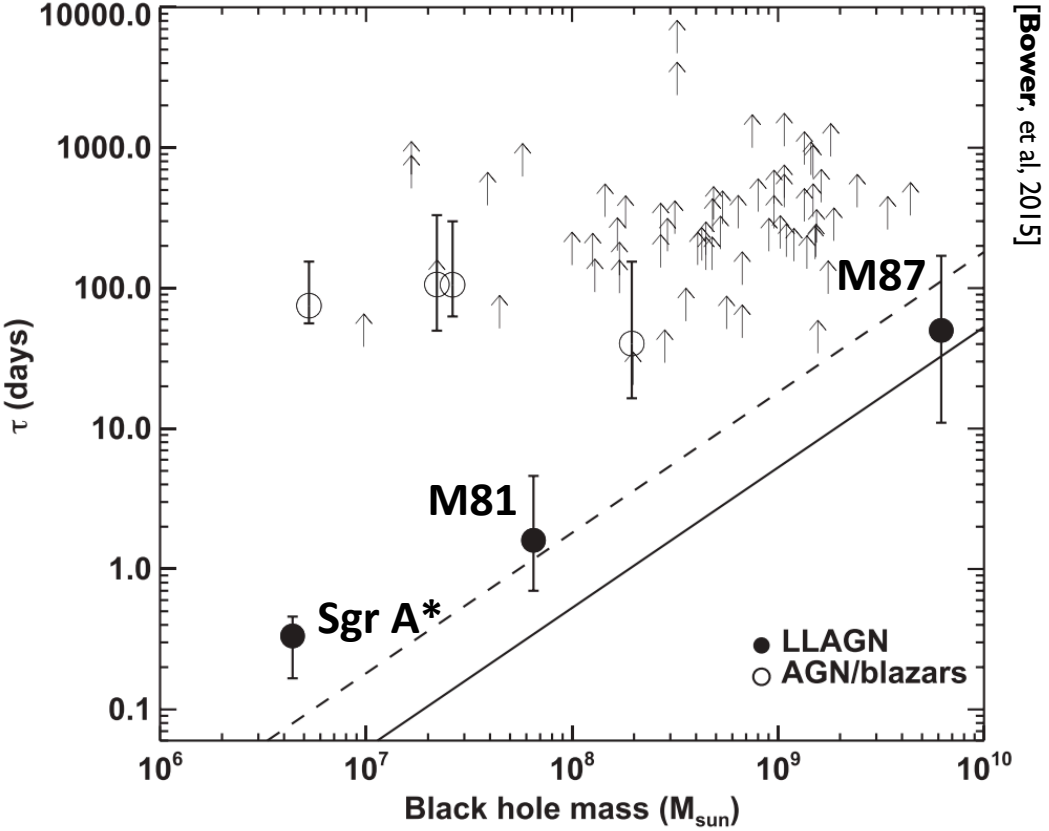
- Multi-wavelength SEDs from core of the compact jet in XRBs & SMBHs w/ ~simultaneous X-ray
- Correlation between jet-break frequency (transition to low τ) and X-ray PL index (hot corona)
- Suggests intrinsic connection between the plasma close to the BH and the outflow

Sgr A*: Highly Variable Source

[**Genzel**, et al. 2003; **Yuan** et al. 2004]



Variability Timescales

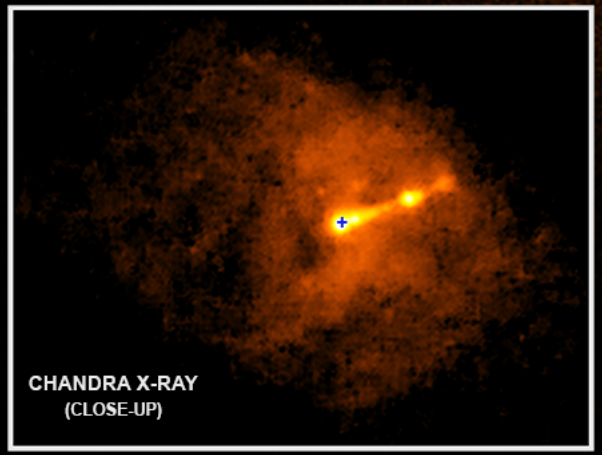


[Bower, et al, 2015]

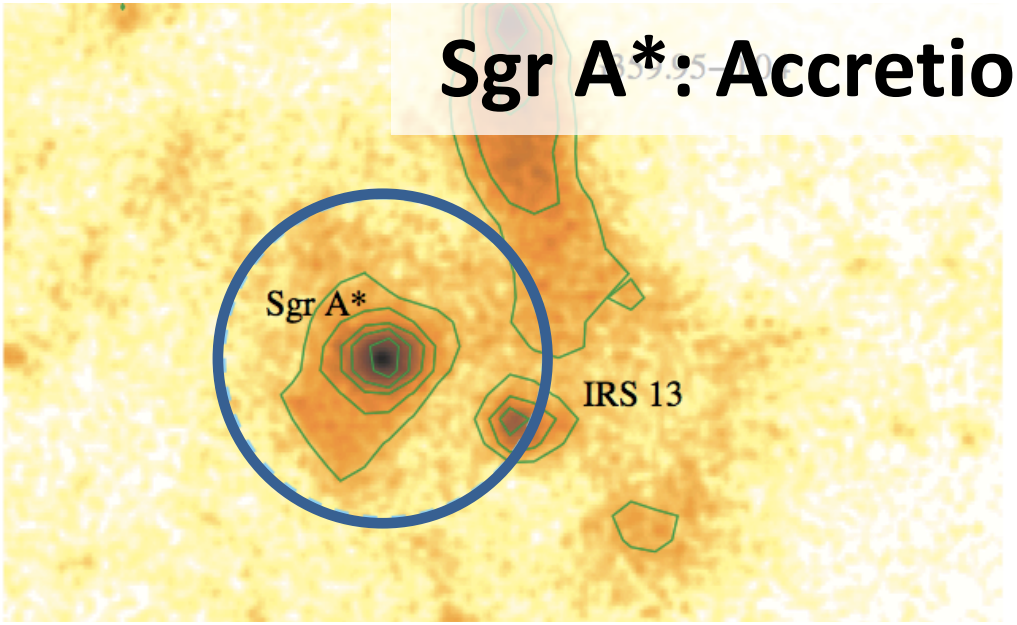
X-ray Vision

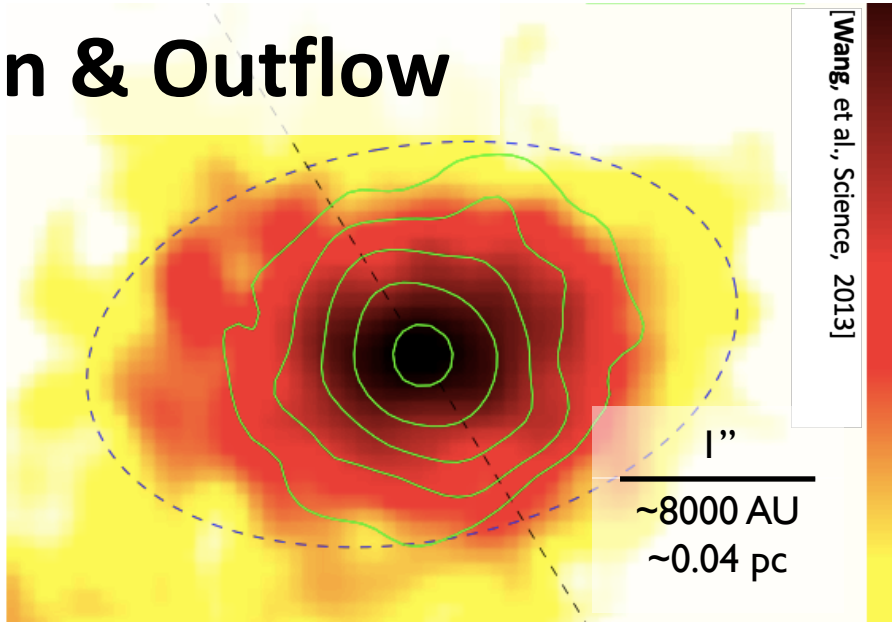
M87 w/ EHT & Chandra

And… Sgr A*?

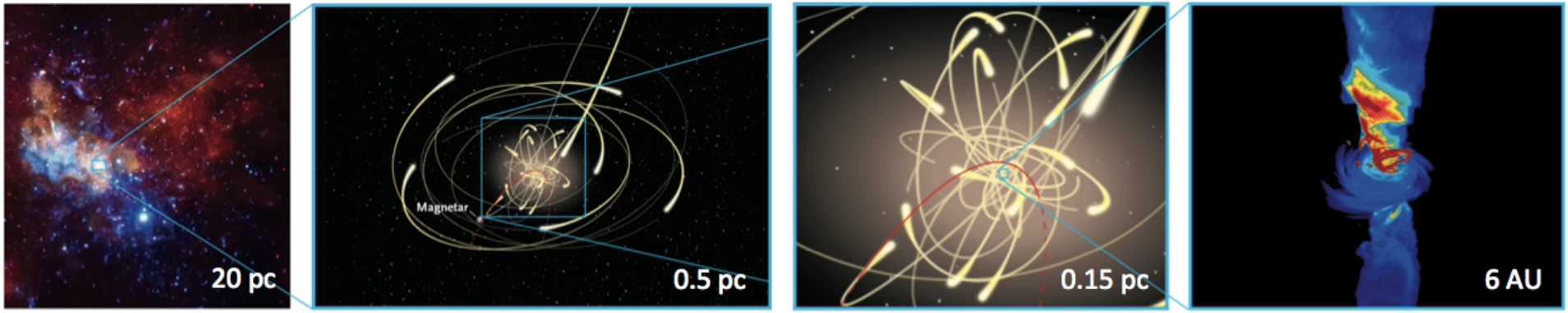


Sgr A*: Accretion & Outflow



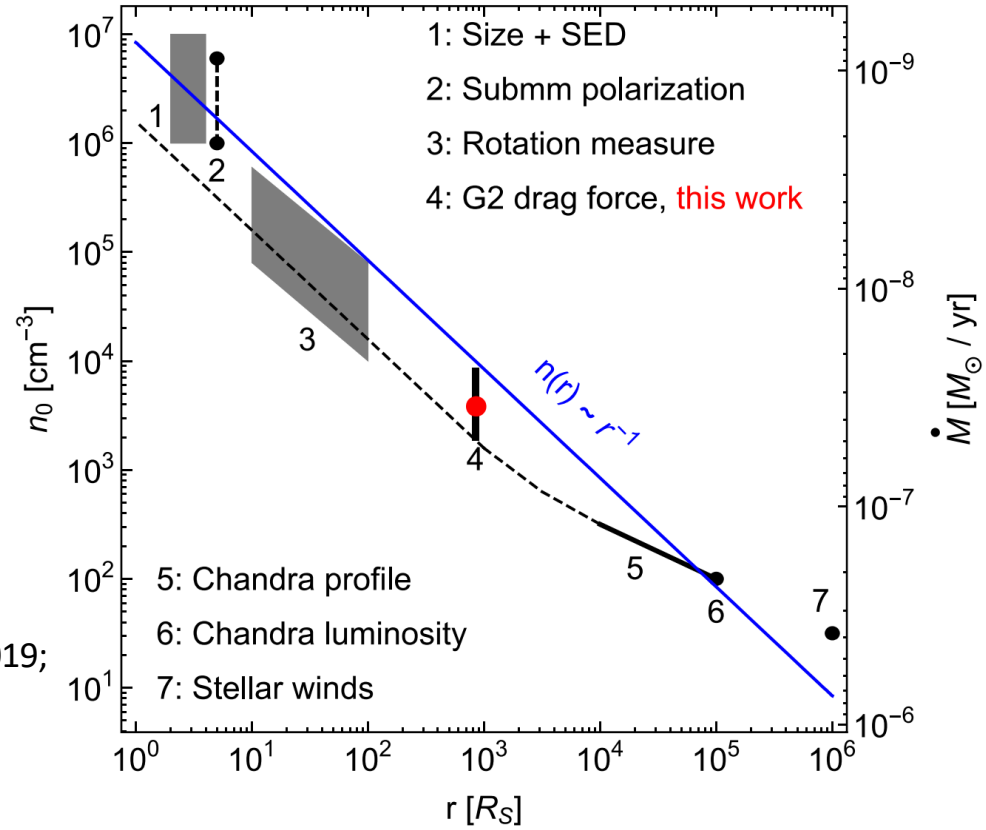


[**DH** & **Bower**, Sky & Tel, 2016]

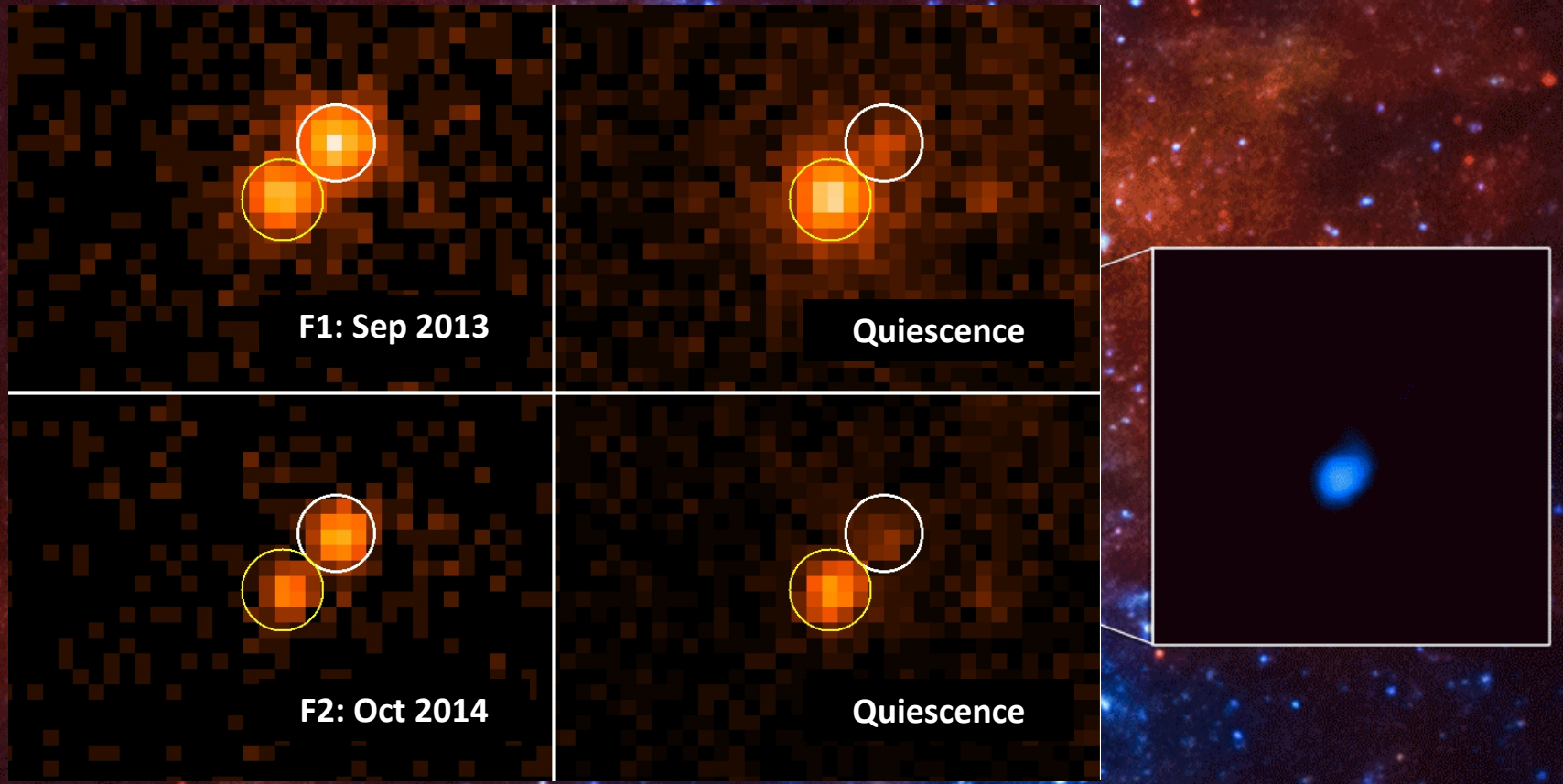


Sgr A*: Bondi to the Event Horizon

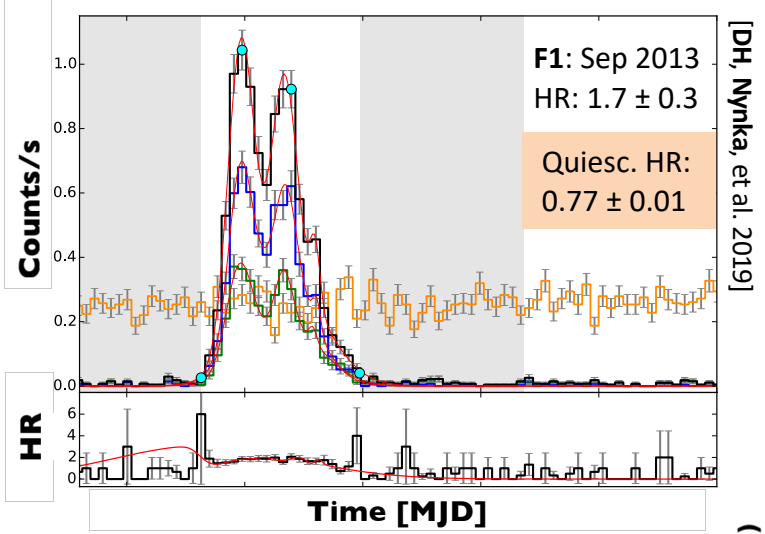
$\dot{M}$ ~ n v R^2 ~ $R^{3/2-a}$ for n ~ R^{-a}, v ~ $R^{-1/2}$



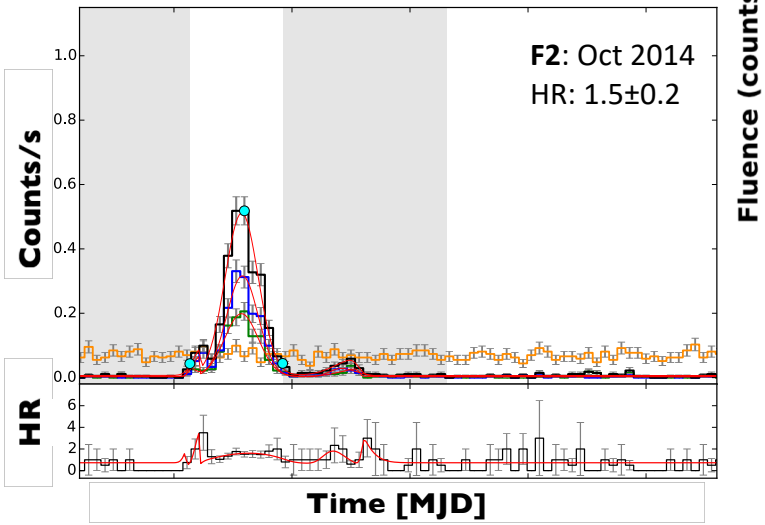
Gillessen+2019;
Pfuhl+2015,
Plewa+2017

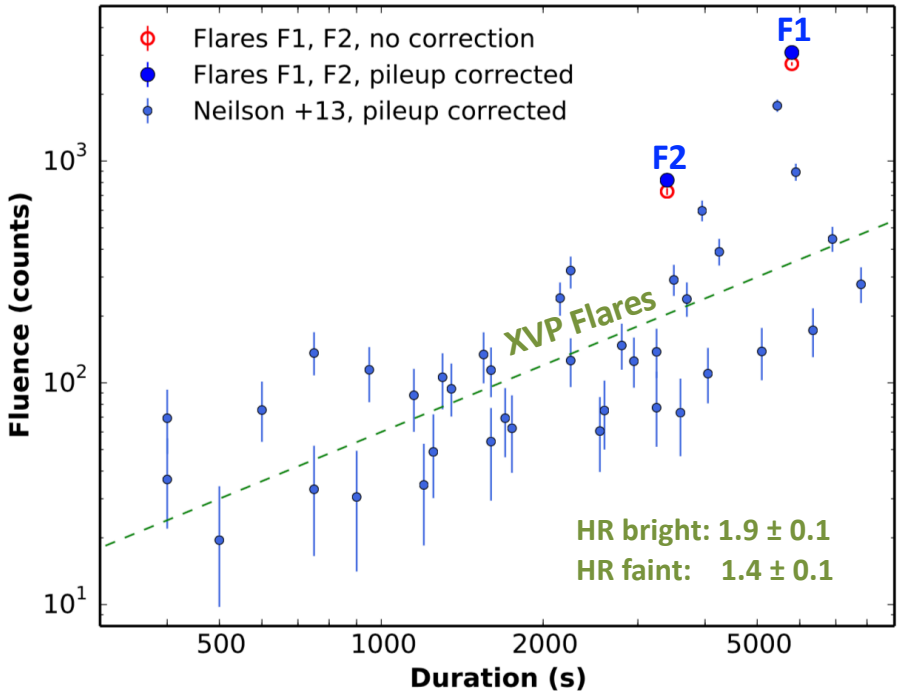

F1: Sep 2013
Quiescence
F2: Oct 2014
Quiescence

Sgr A* Bright *Chandra* Flares



[DH, Nynka, et al. 2019]

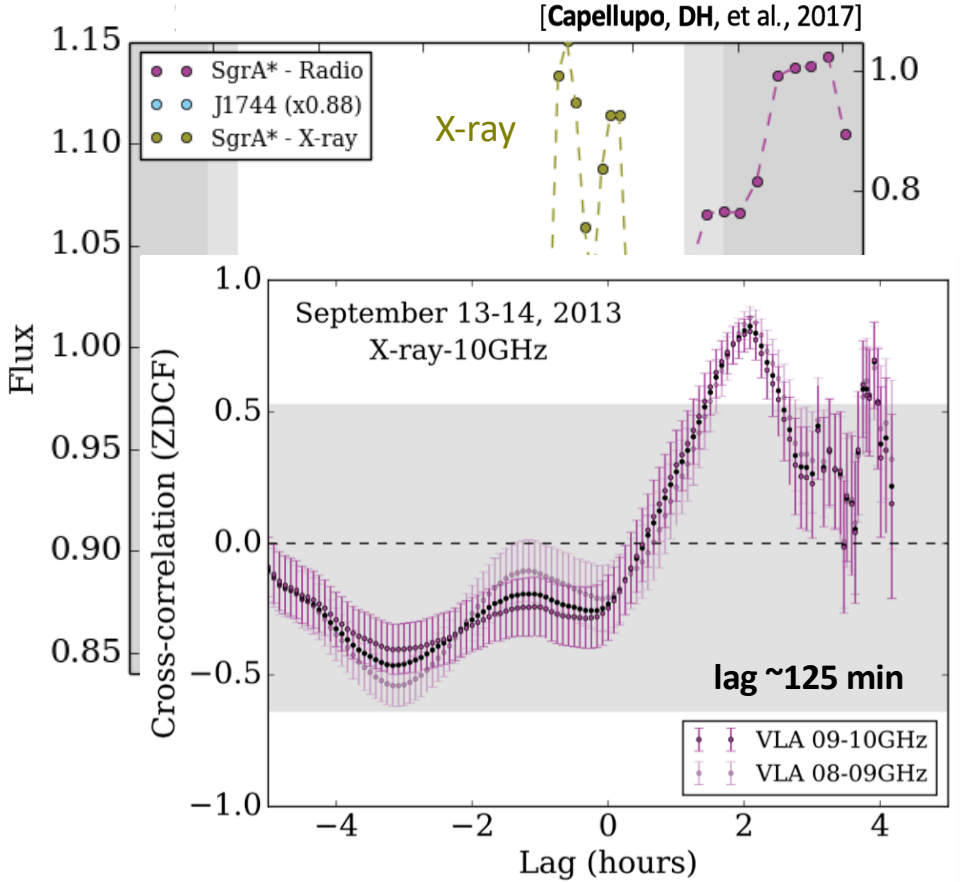


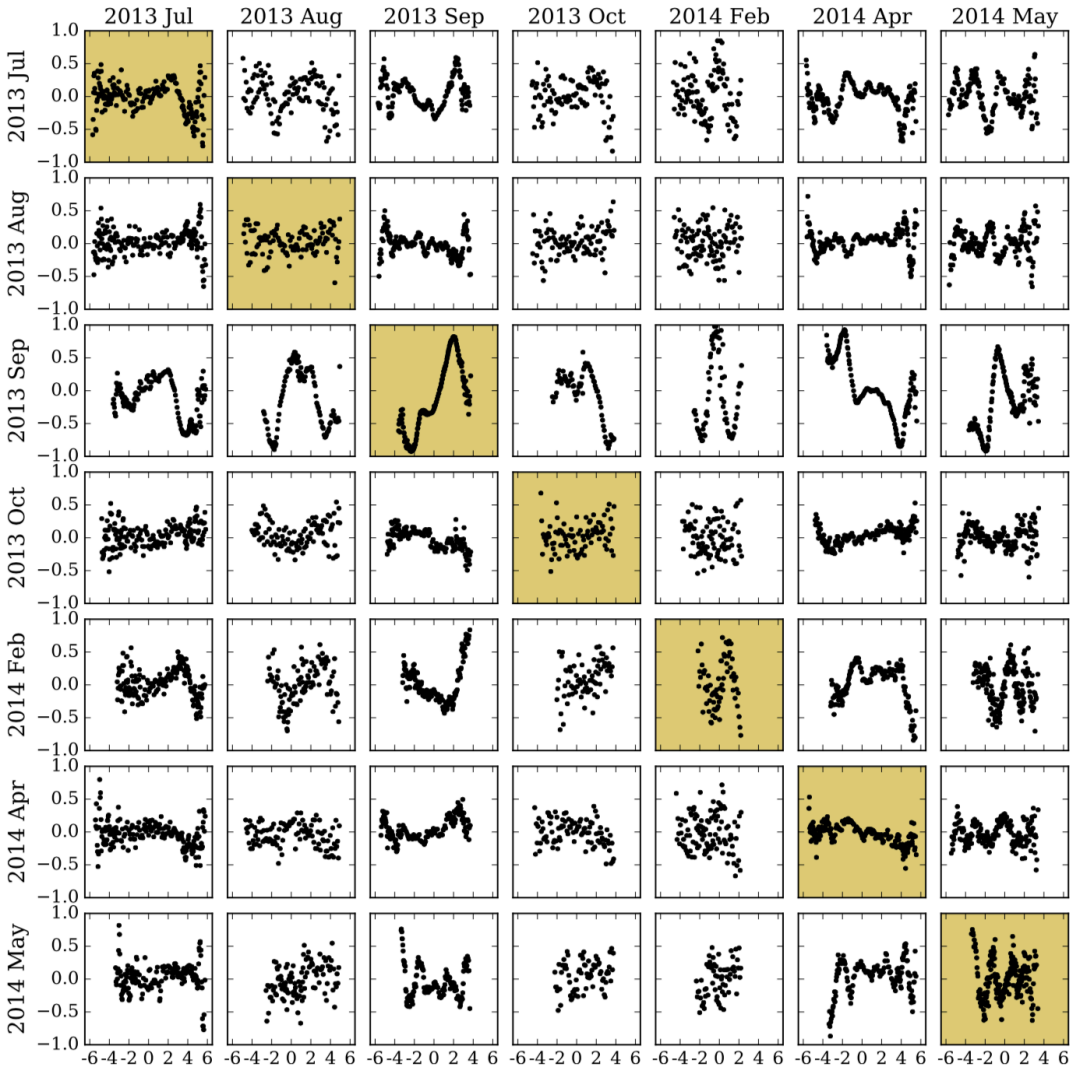



Plus Radio Eyes

Simultaneous *Chandra*/VLA Obs

- Simultaneous *Chandra* + VLA data
- Radio flux increase of 25% (3.6 cm; 8-10 GHz)
- Anti-correlation at X-ray rise? (e.g., Dodds-Eden+2009)
- Cross correlation peak ~125 min
- Consistent with previous time delay estimates

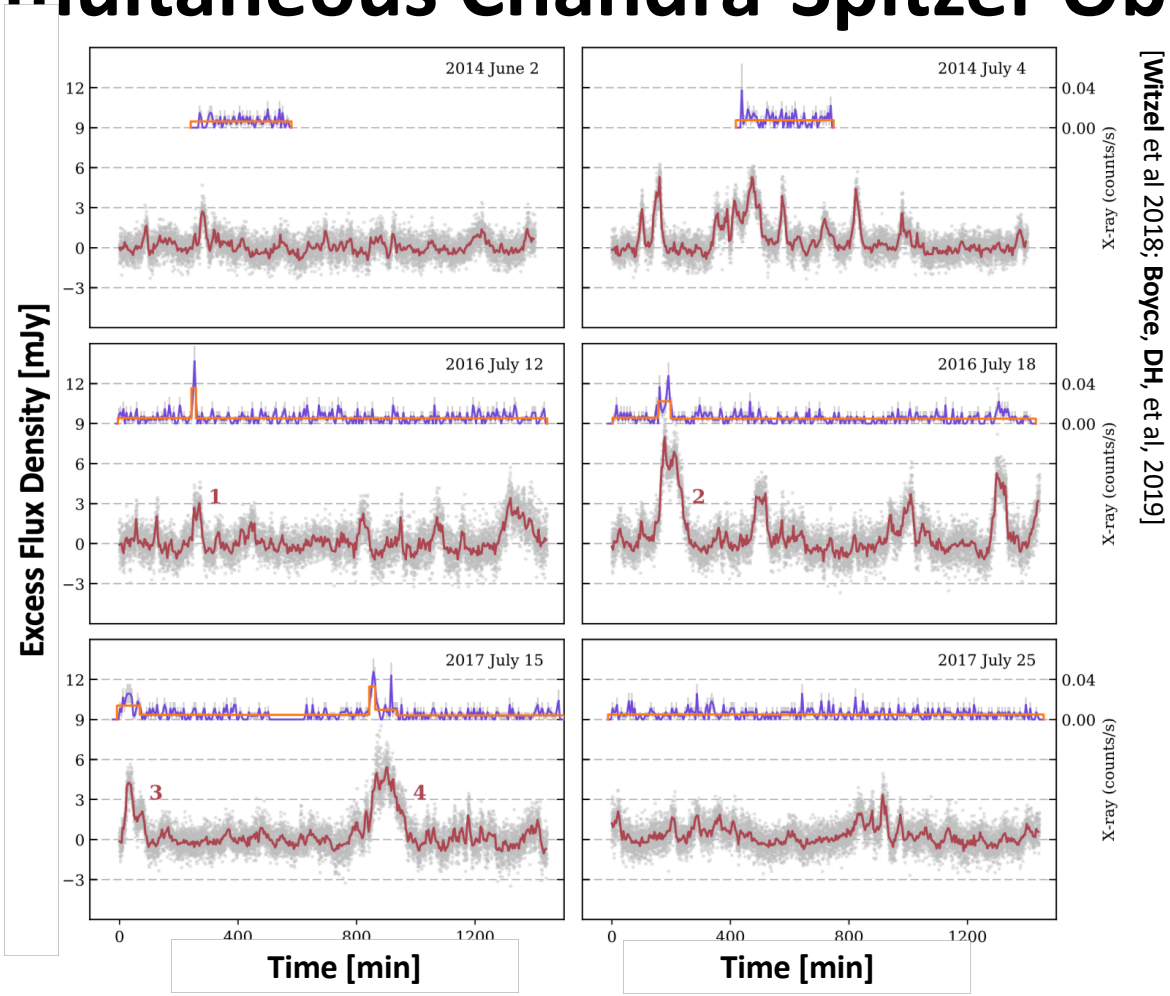




[Capellupo, DH, et al., 2017]

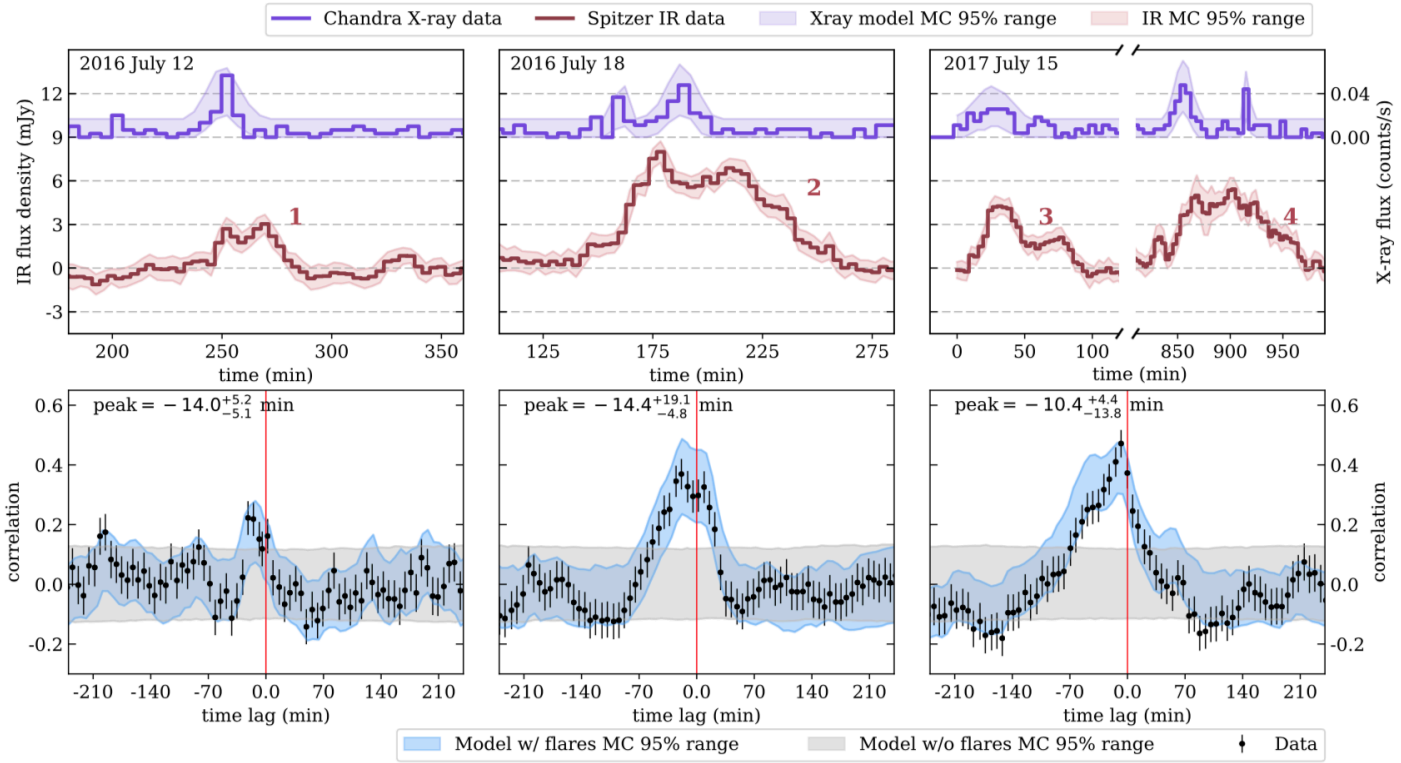
The IR Perspective

Simultaneous Chandra-Spitzer Obs



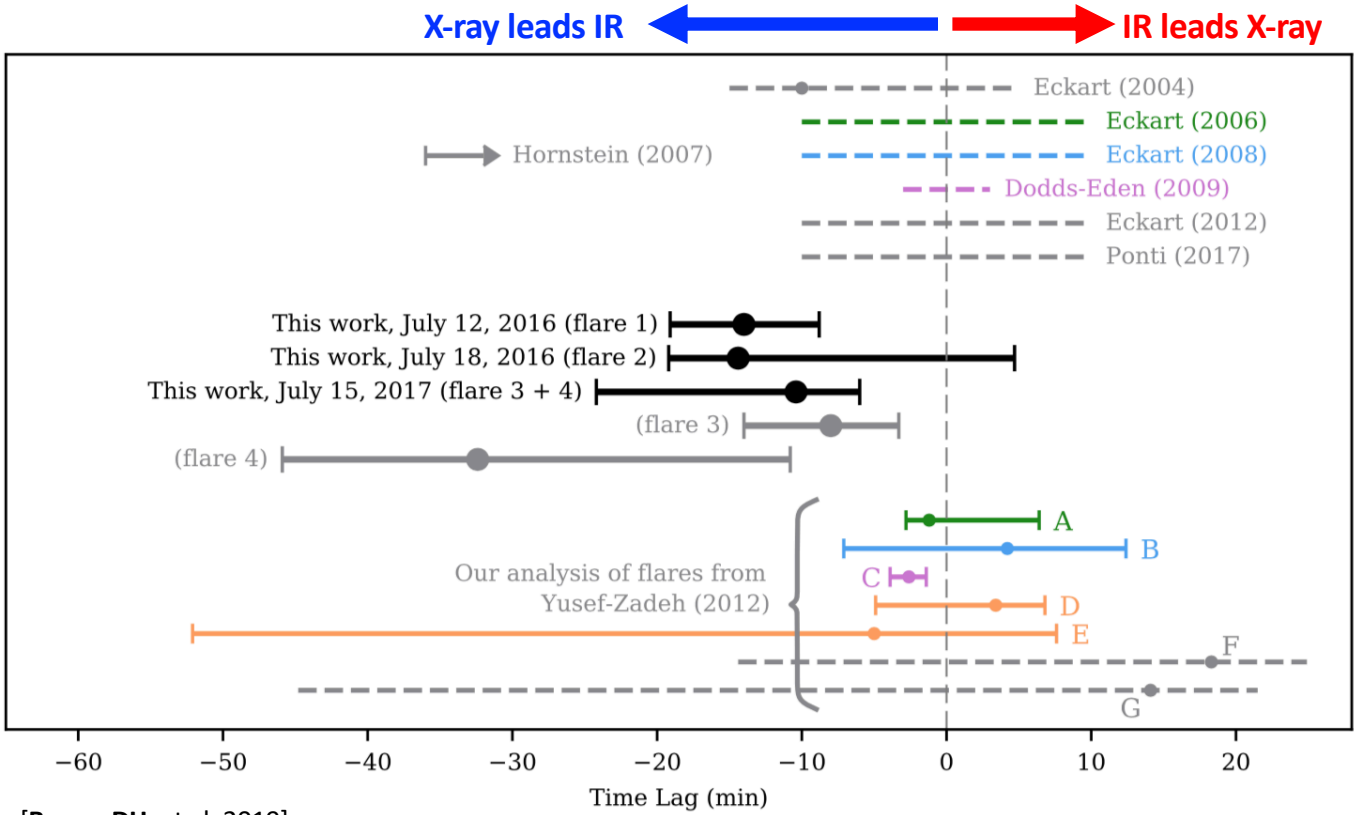
[Witzel et al 2018; Boyce, DH, et al, 2019]

X-ray/IR Cross-Correlations (ZDCF)



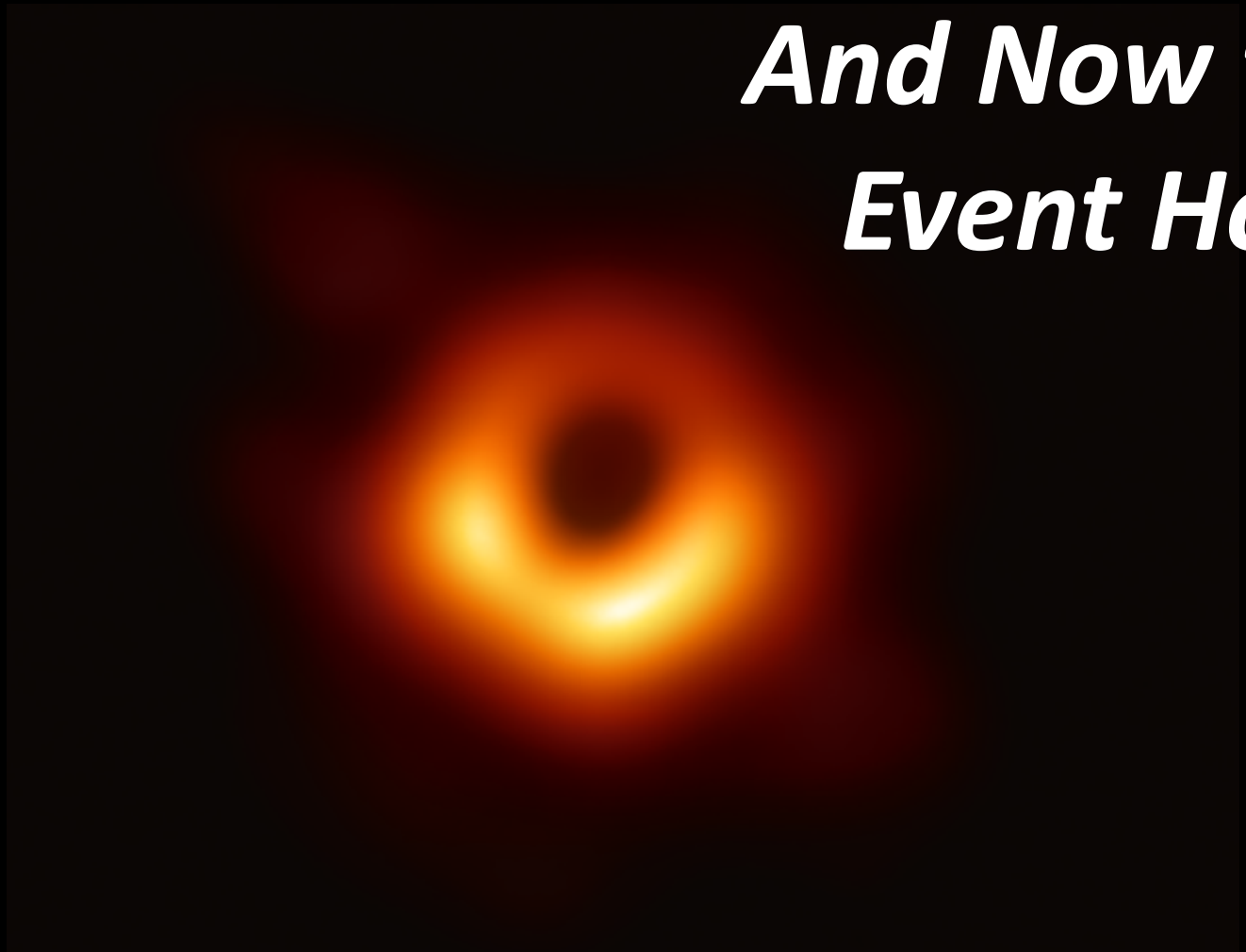
[**Boyce**, **DH**, et al, 2019]

X-ray/IR Timelags



[**Boyce**, **DH**, et al, 2019]

And Now to the Event Horizon

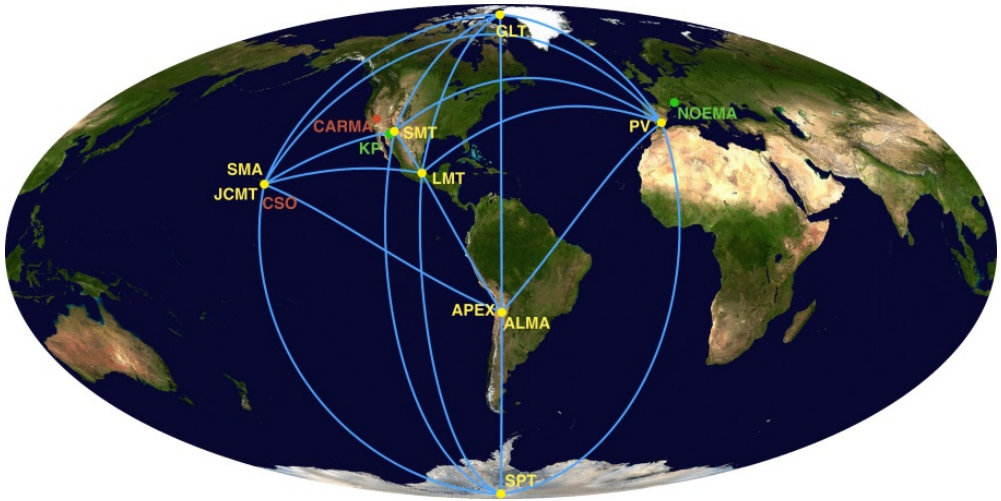


Approaching the Event Horizon

- Known Mass & Distance: BH shadow ~ 50 microarcseconds
- High S/N on timescales ~ r_g/c (20 sec)

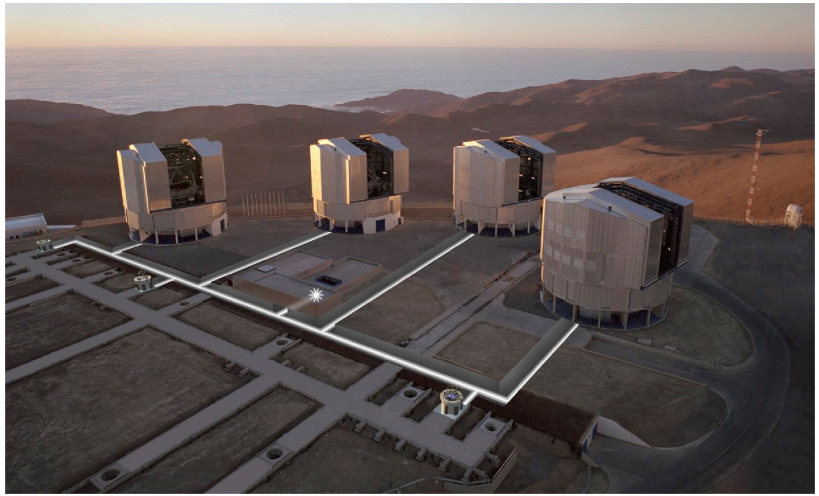
Slide credit: J. Dexter

Event Horizon Telescope



λ ~ 1 mm, B ~ 10000 km
θ ~ 20 μas

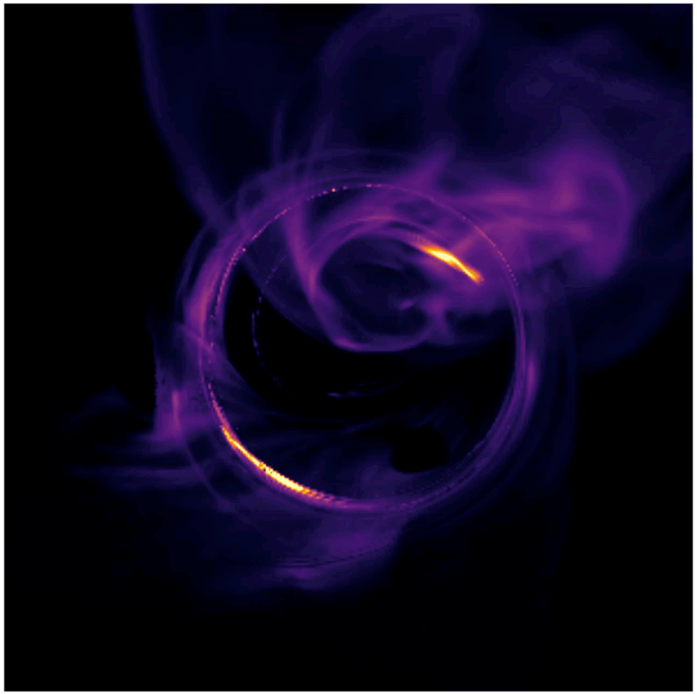
VLTI GRAVITY



λ ~ 2 micron, B ~ 100 m
θ ~ 4 mas

New Sgr A* VLT/GRAVITY NIR Flares

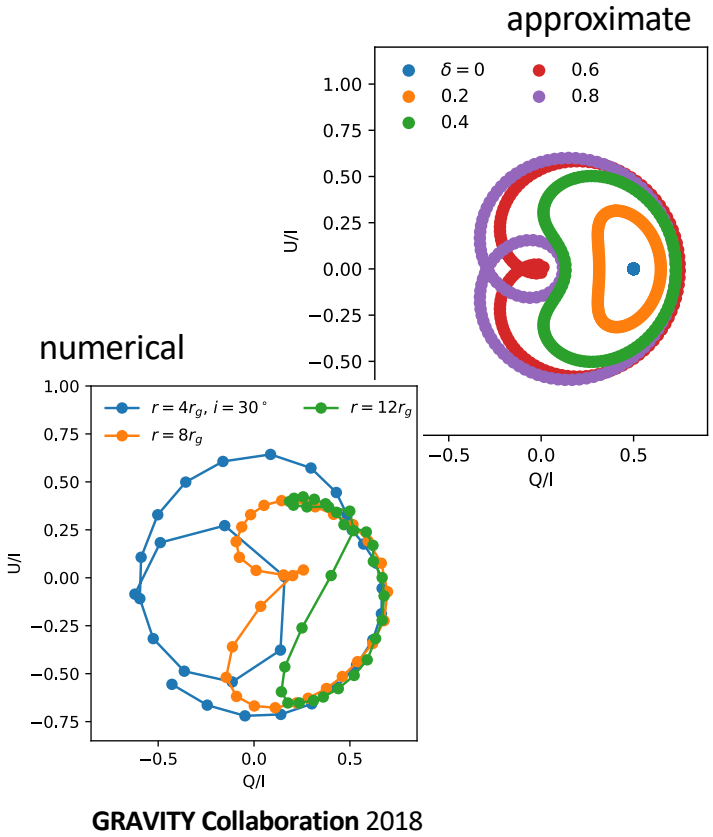
GRAVITY Collaboration 2018



Direct measure of Sgr A*'s black hole event horizon/ISCO?!?

- Monitoring S0-2 during periapse
- 3 NIR flares detected from Sgr A*'s accretion flow
- Energetics consistent with magnetic reconnection or mag. shocks between e^- and hot gas near ISCO
- Flare durations 30-90 minutes, similar to e^- cooling time or dispersal due to diff. rotation
- Peak flux 2x Sgr A*'s median K_s-band flux (similar to S0-2)

NIR Flare Orbital Models

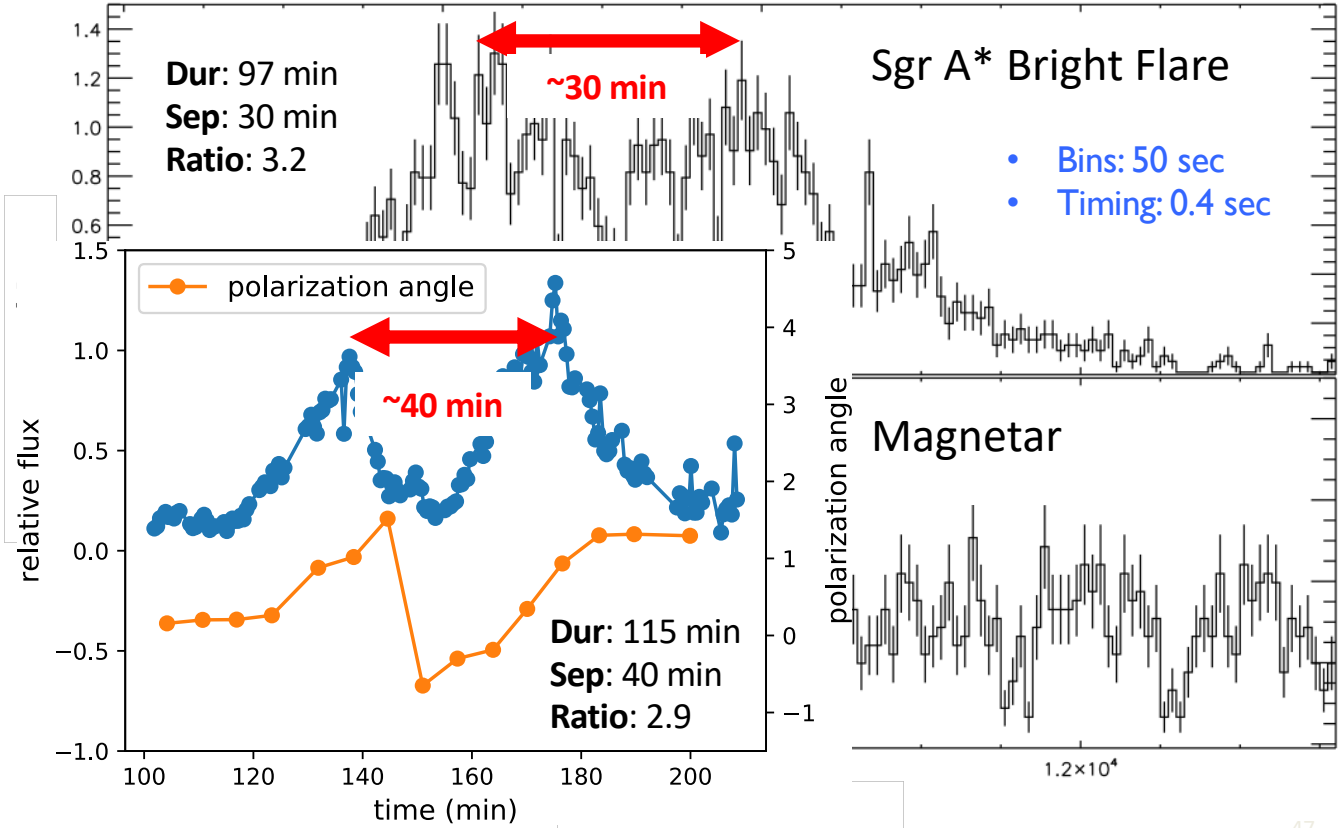


GRAVITY Collaboration 2018

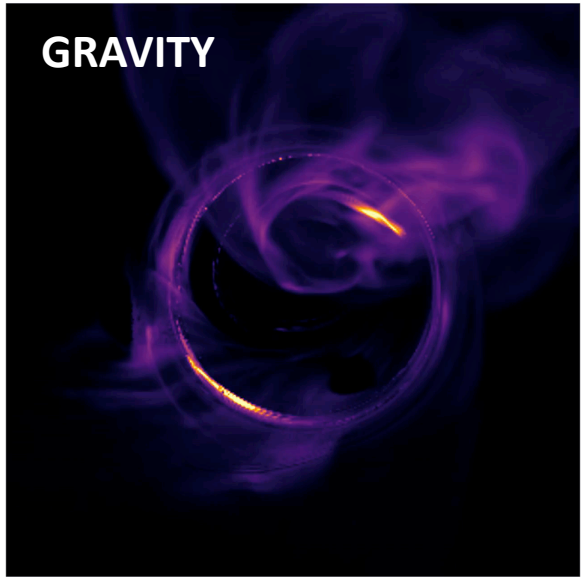
- Long flares allow GRAVITY to trace more than ½ closed orbit
- Hot spots moving at ~0.3 c
- Orbital solutions consistent with face-on orbit (!?!)
- All three flare orbits fit with same orbital model for Kerr BH (spin=0) with $M_{BH} = 4 \times 10^6 M_{sun}$
- Orbital radius 6-10 r_g for periods 33-65 min
- High BH spin solution also allowed, but would imply retrograde orbits

F1 Morphology & Timing

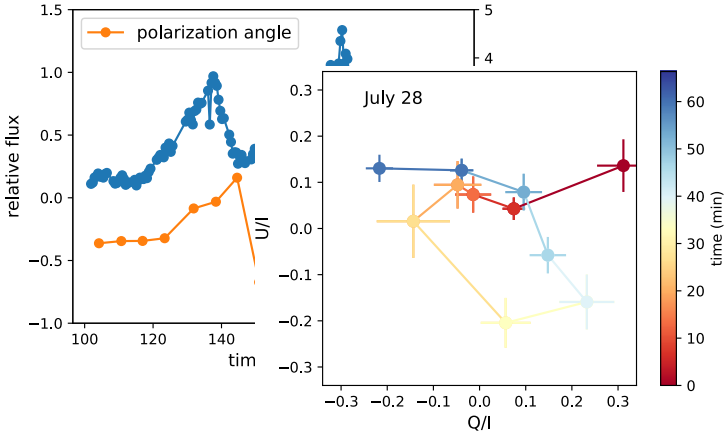
[**DH, Nynka**, et al. 2019]



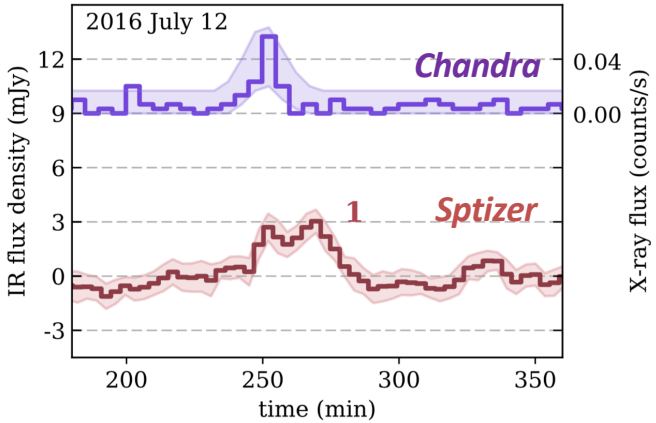
GRAVITY Collaboration 2018

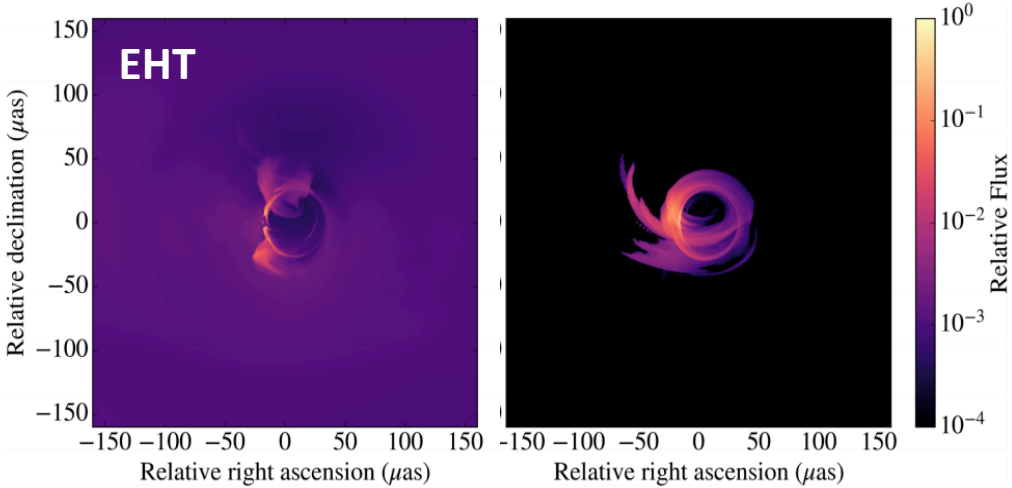


- Multiwavelength Coordination with the **Chandra**, **Spitzer**, **VLA** and **GRAVITY**?!
- Changes in radiative output ←→ changes in structure **at the event horizon**



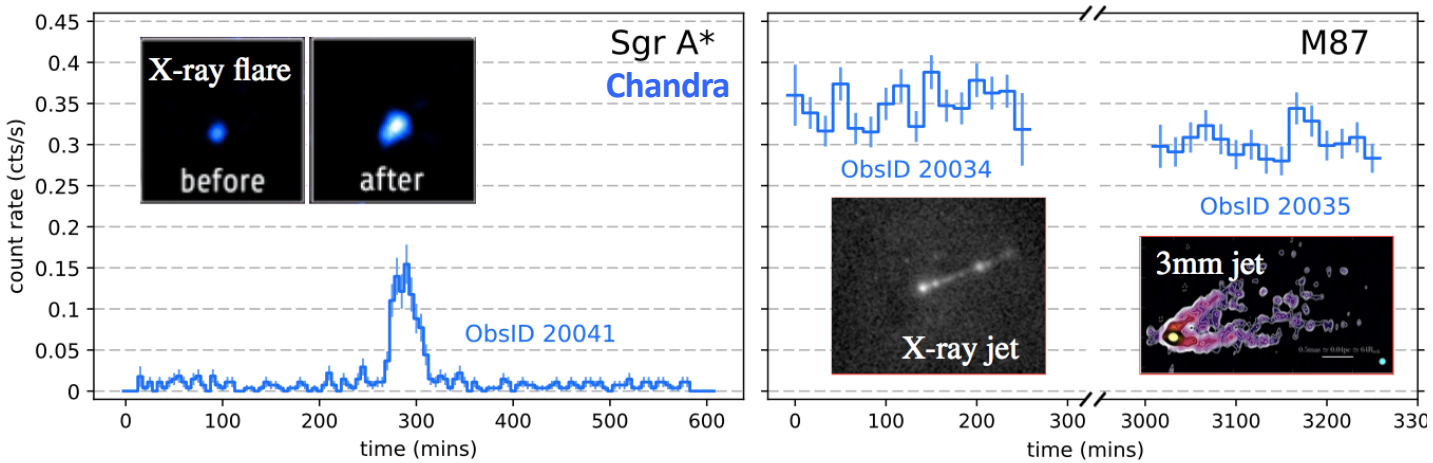
[**GRAVITY Collab** 2018; **Boyce** et al. 2018]

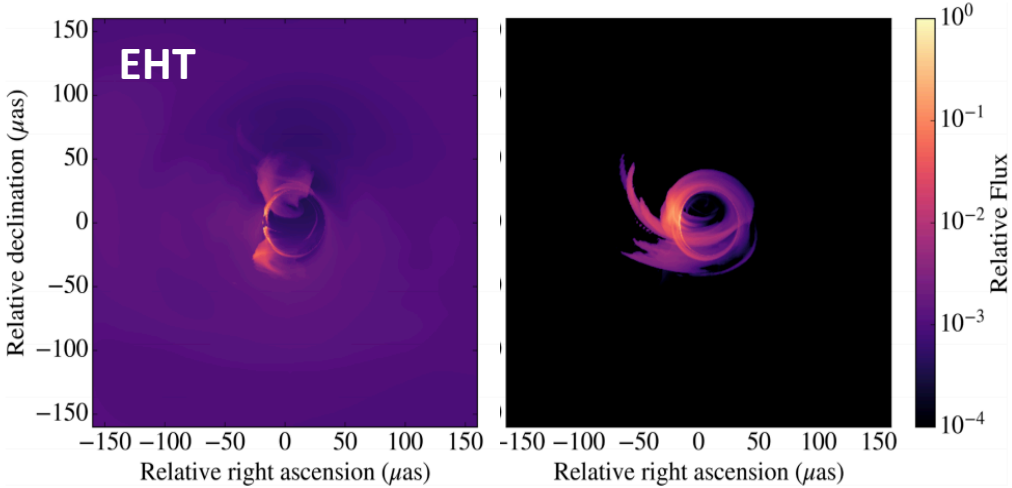




- Multiwavelength Coord. 2017/2018 w/ **EHT**, **Chandra**, **NuSTAR**, **VLT**,++
- Campaigns are ongoing:
  - Chandra, NuSTAR, GRAVITY Apr 2019
  - Chandra, Spitzer Jul 2019
  - Joint w/ EHT Mar 2020

[**Ball**, et al. 2016; **Boyce** et al. 2018; **M. Johnson** for **EHT MWL WG (Markoff & Hada)** 2018]





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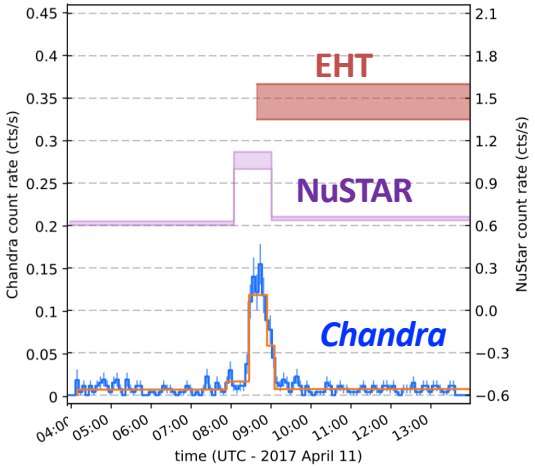

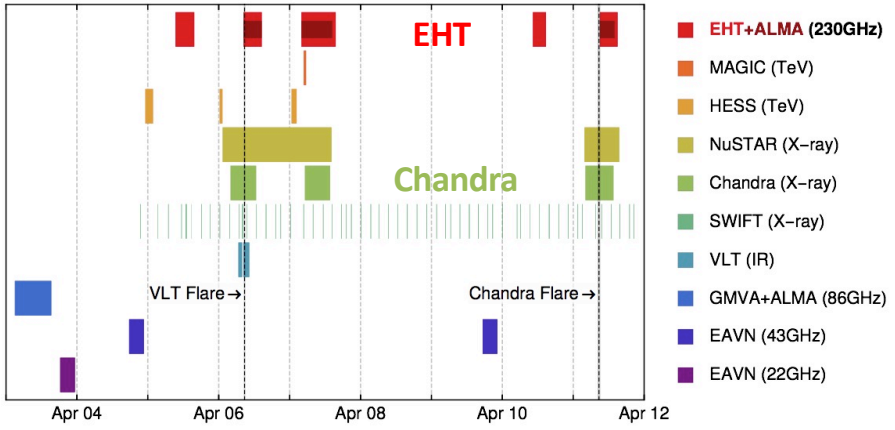


THANKS!