Flows and Flares around the Nearest Massive Black Hole -- Sgr A*

Q. Daniel Wang

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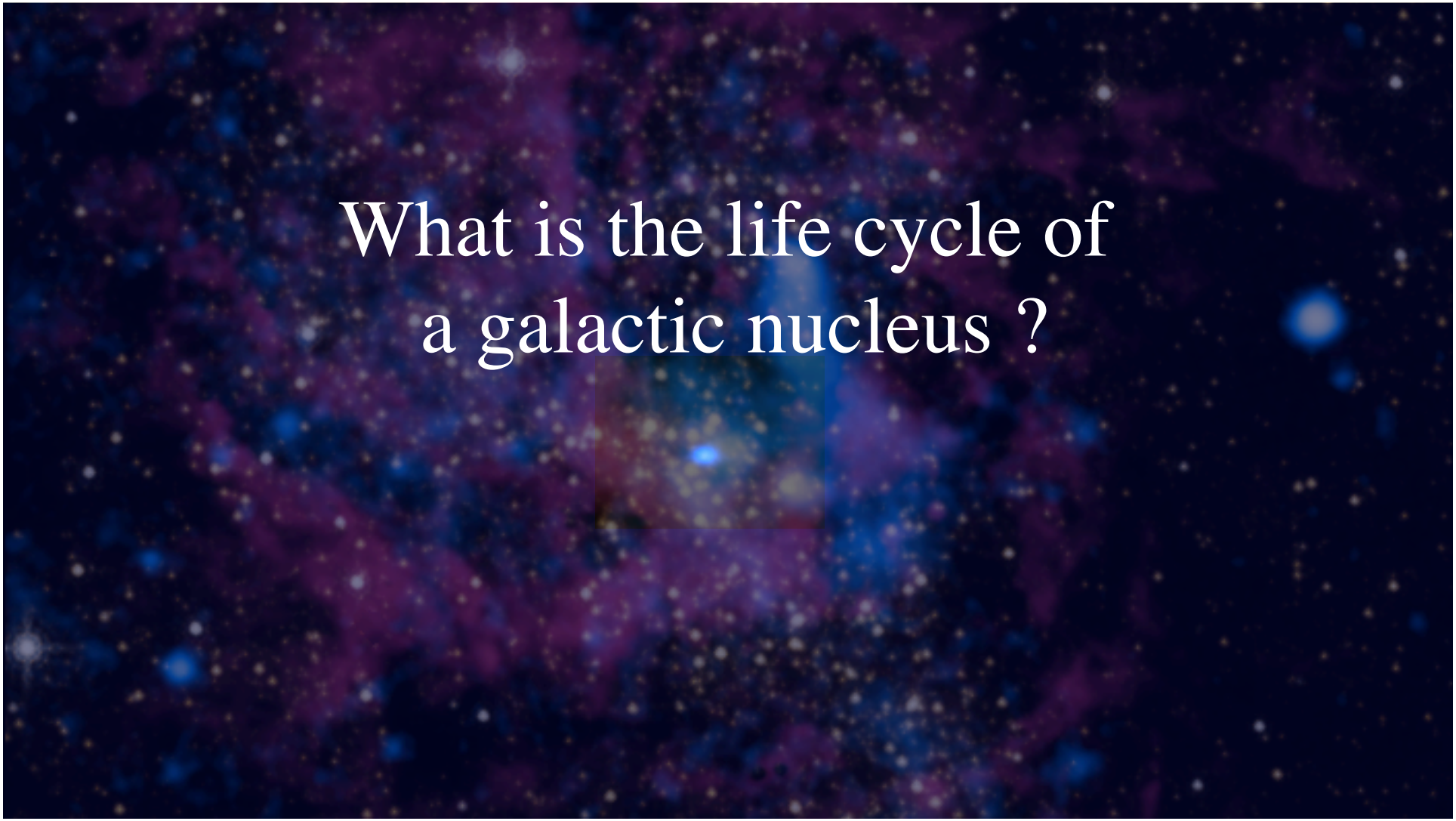
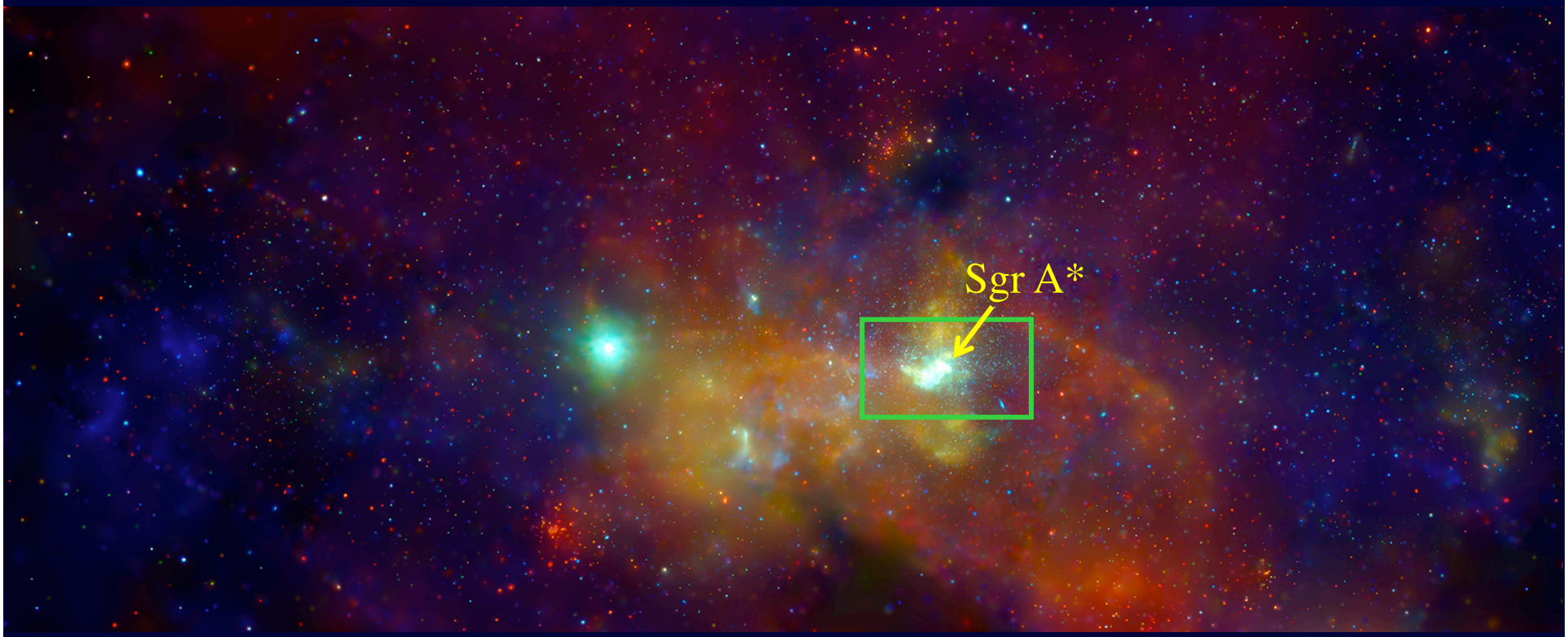

What is the life cycle of
a galactic nucleus ?

The Galactic center as viewed by Chandra



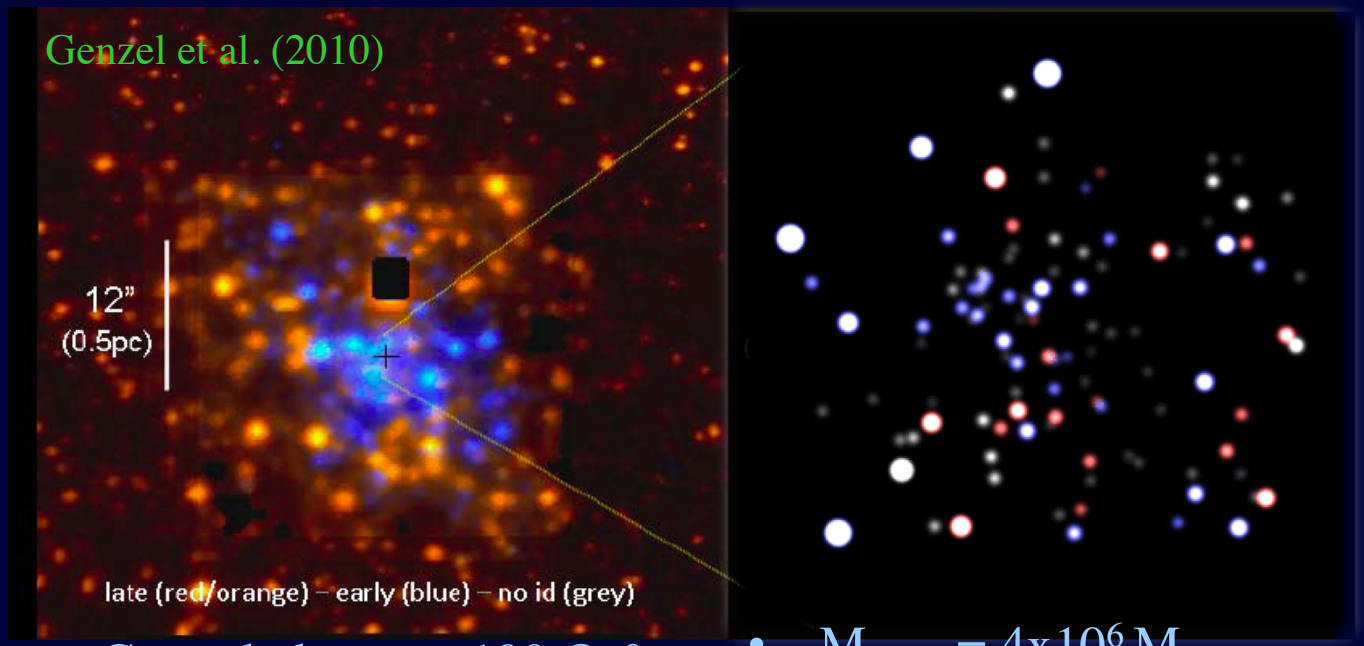
Red: 1-2.5 keV Green: 2.5-4 keV Blue: 4-9 keV

Wang et al. 02

The Galactic center in NIR

HST/NICMOS Pα + continuum map (Wang et al. 10)

The Galactic center in NIR

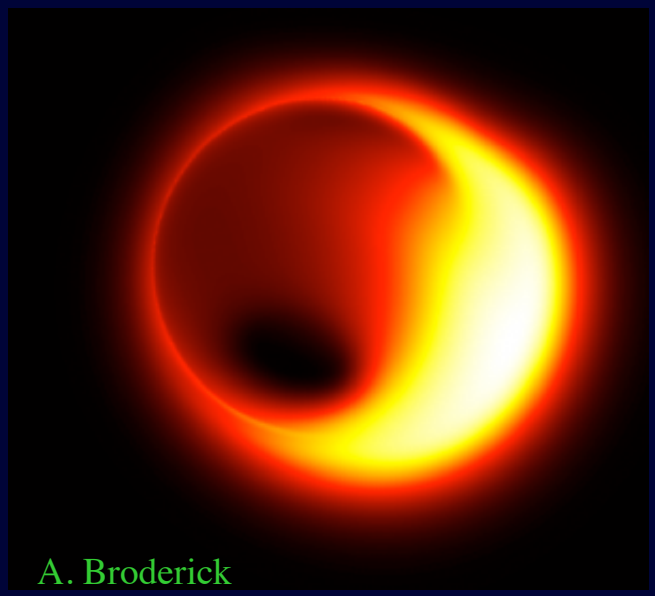


- Central cluster: ~100 O & WR stars, many in a disk
- Colliding stellar winds → 10^7 K gas

- $M_{MBH} = 4 \times 10^6 M_\odot$
- $L_x = 3 \times 10^{33}$ erg/s
- L_{bol}= a few $\times 10^{36}$ erg/s or ~ $10^{-8} L_E$ -- peaking in submm!

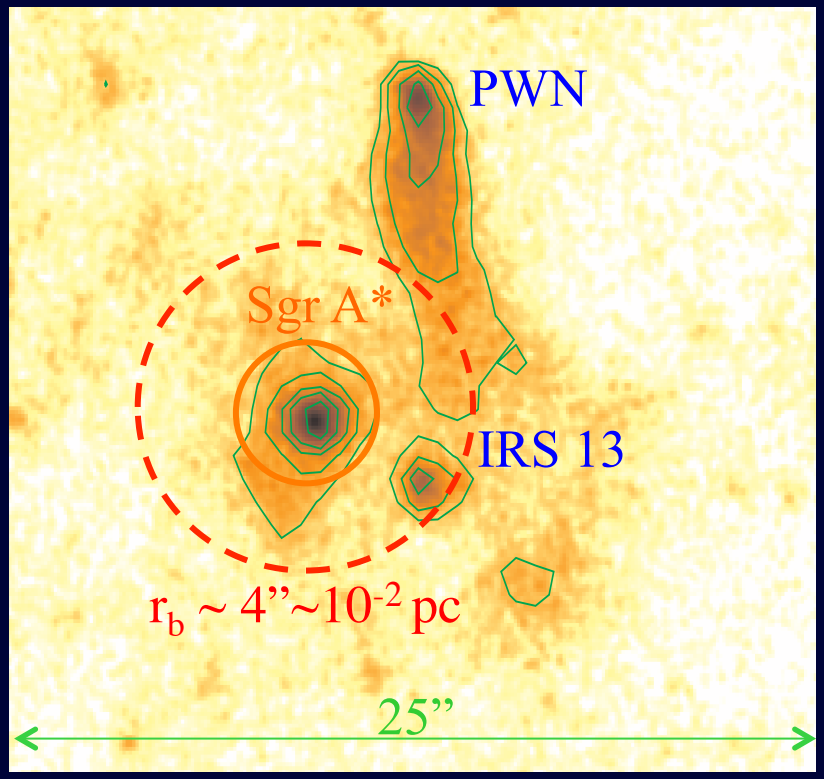
What you wish to see Sgr A* at (sub)mm

https://blackholecam.org/research/bhshadow/


A. Broderick

- (sub)mm emission arises in the innermost region ($r < 10^2\ r_s$)
- Its morphology depends on as the spin of the MBH, as well the accretion and emission models.

Sgr A* in X-ray



1-9 keV image from 3 Ms Chandra XVP (2012)

Hot gas accretion rate

$\dot{M}_b \sim 2 \times 10^{-5}\ M_\odot/\mathrm{yr}\ (M_{MBH}/4\times10^6 M_\odot)^2\ (n_e/10^2\ \mathrm{cm}^{-2})(T/10^7\mathrm{K})^{-3/2}$

$\Rightarrow L_b \sim 2 \times 10^{41}$ erg/s (assuming a 10% radiative efficiency) or $\sim 10^5$ greater than L_{bol} of Sgr A*.

So it is a radiatively inefficient accretion flow (RIAF)!

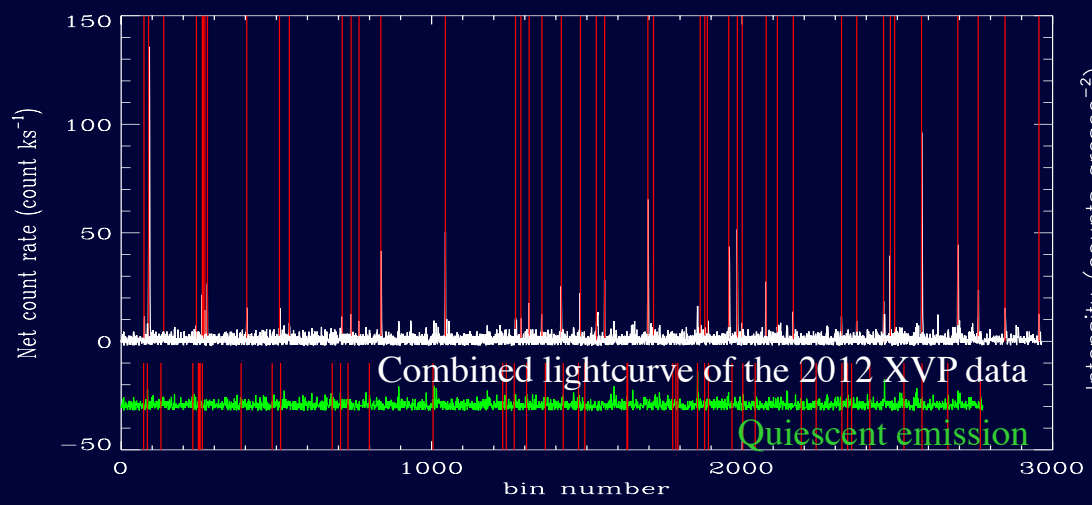
Where does the energy go? Or

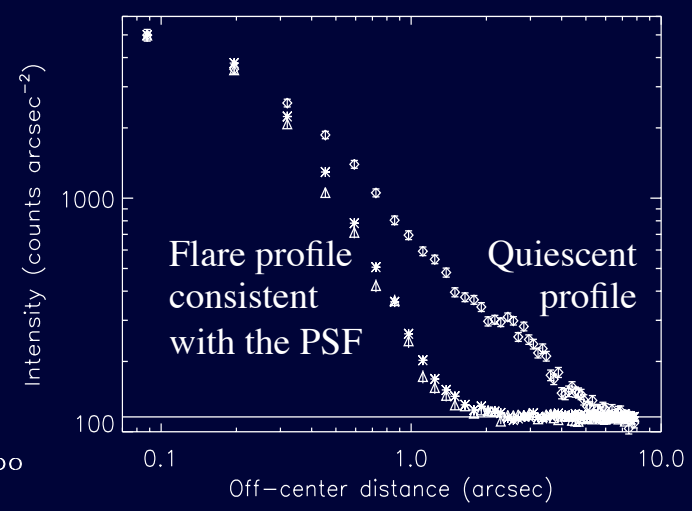
is there much of accretion at all?

Wang et al. 13

Dissecting X-ray emission of Sgr A*

Decompose flare and quiescent components

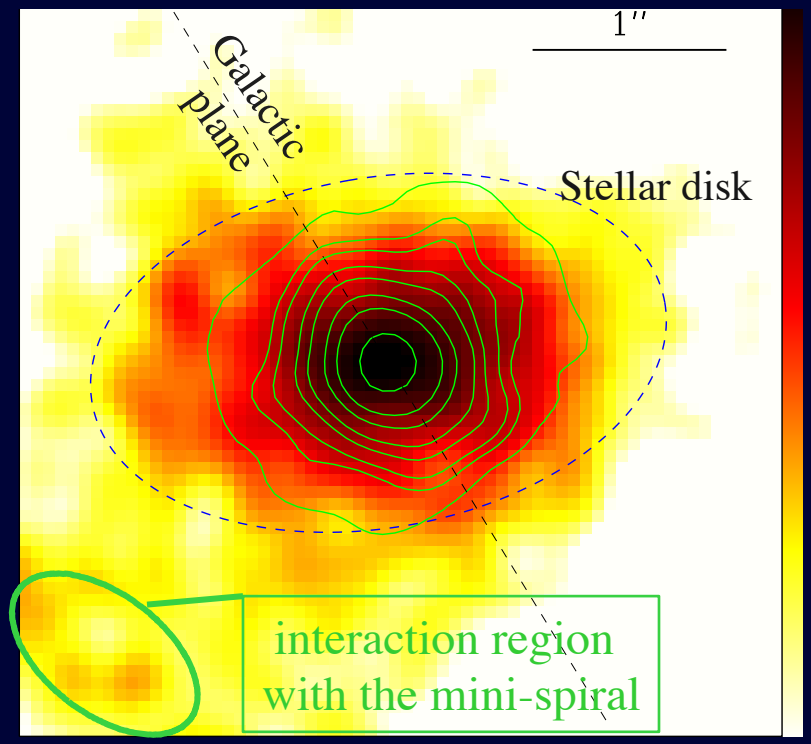




- Detected flares account for ~1/3 of the total X-ray flux.
- Flare emission is point-like.
- Quiescent emission is extended on 4” scales.

Wang et al. 13; Neilsen et al. 13; Yuan & Wang 16

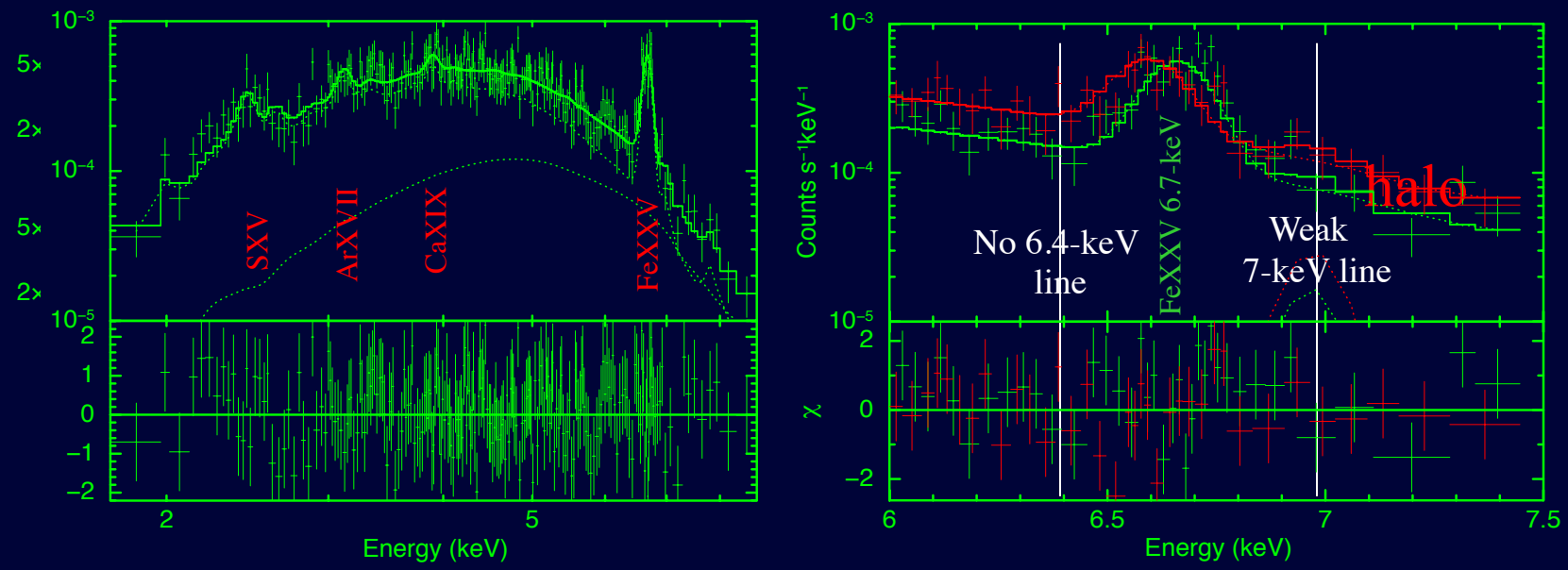
Model the quiescent X-ray emission



- Residual point-like component < 20% of the flux within 1.5” radius.
- Elongation of the extended component is consistent with the orientation of the stellar disk.
- Apparent enhancement due to the wind interaction with the mini-spiral of cool gas.

Wang et al. (2013)

X-ray spectral testing of RIAF solutions



- ADAF solution without mass-loss → inconsistent large FeXXVI/FeXXV Kα ratio, too flat continuum, & too low metal abundance.
- Best-fit model requires mass-loss > 99% -- the prediction of the adiabatic inflow-outflow solution (e.g., Blandford & Begelman 04).

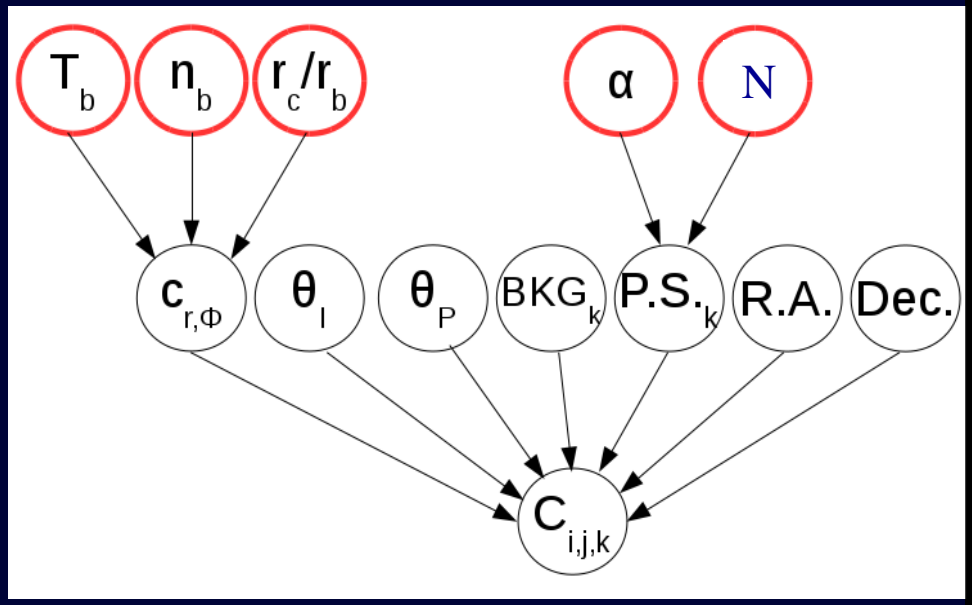
Summary: 1-D X-ray dissection results

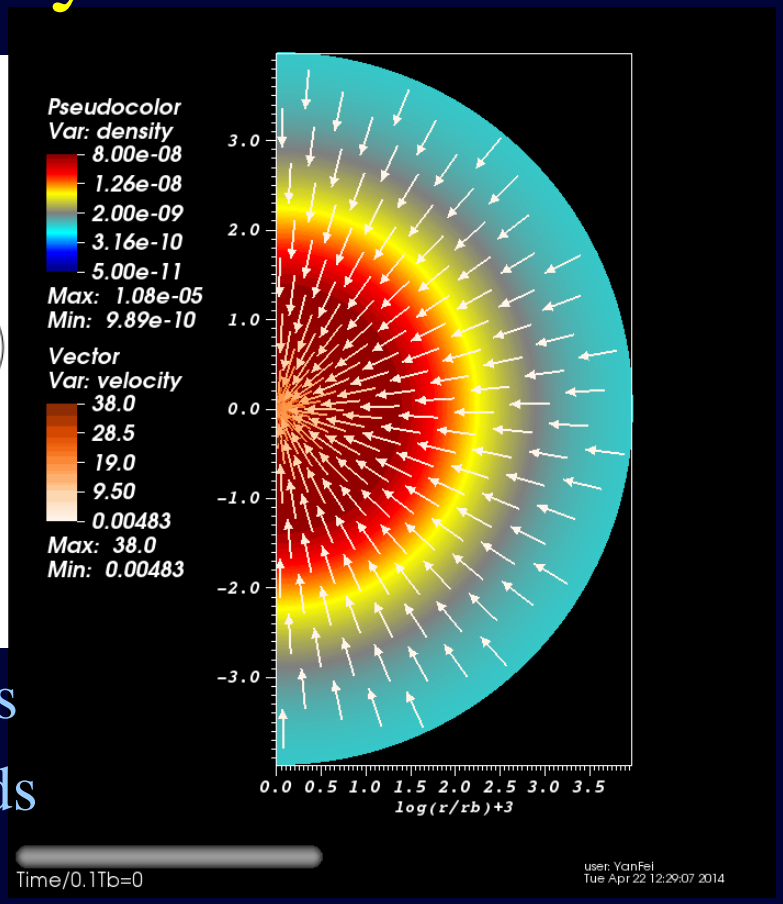
- No indication for any cold accretion!
- Bulk of the quiescent X-ray emission is **optically-thin thermal** and arises from **outer regions** ($r \sim 10^4$-$10^5\ r_s$) of the accretion flow.
- Contrast to AGN, in which innermost regions dominate.
- **Outflow nearly balances the inflow**.

- Why should the outflow occur?
- What is the origin of the central point-like source?

Toward physical modeling of the accretion and outflow

Simulations and Bayesian fit





- Projection
- PSF convolution

⇨ count images in three bands

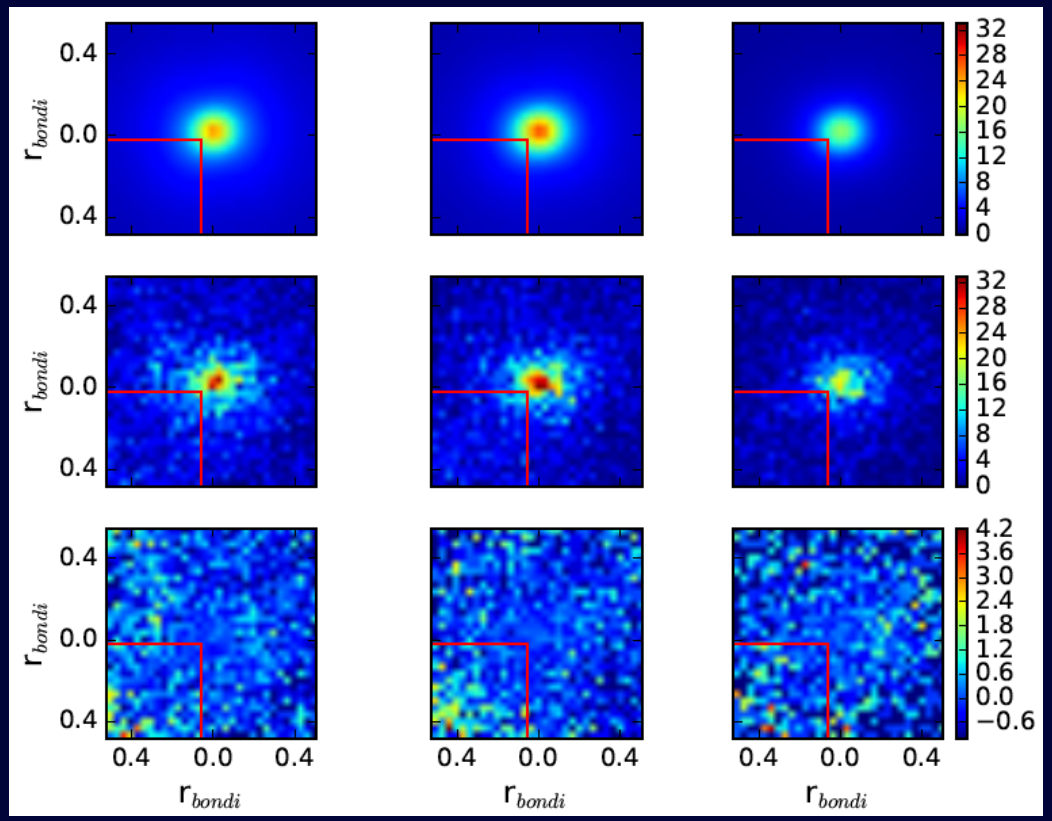
Roberts, Jiang, QDW, & Ostriker 17

Best-fit model compared with data

Model

Data

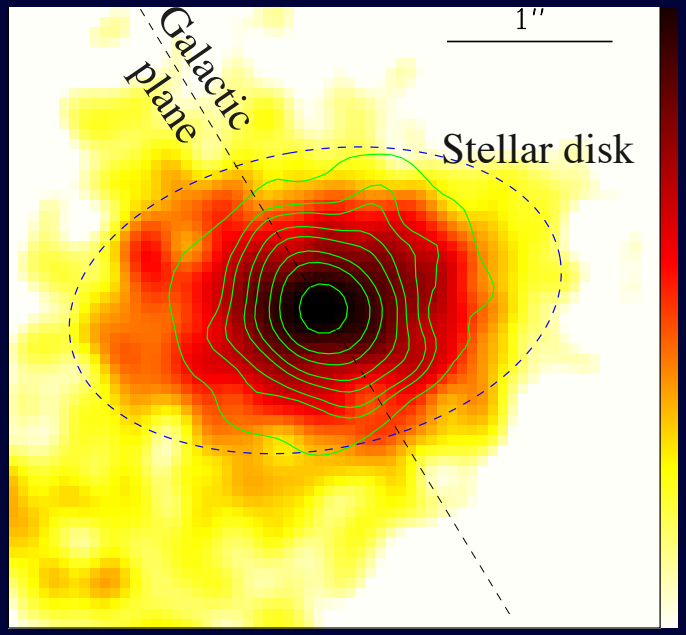
Residual



1-4 keV 4-5.5 keV 5.5-9 keV

Key best-fit model parameters

θ_I (deg.)	126.4 (125.0,127.7)
θ_P (deg.)	99.1 (97.8,100.5)
r_c/r_b	0.058 (0.052,0.064)
T_b (K)	1.30e7 (1.24e7,1.38e7)
n_b (cm^{-3})	187.0 (174.9,197.6)
α	4.95 (3.96,6.76)
$\log_{10}(N)$	2.69 (2.18,3.63)



Consistency between the orientations of the accretion flow and the stellar disk.

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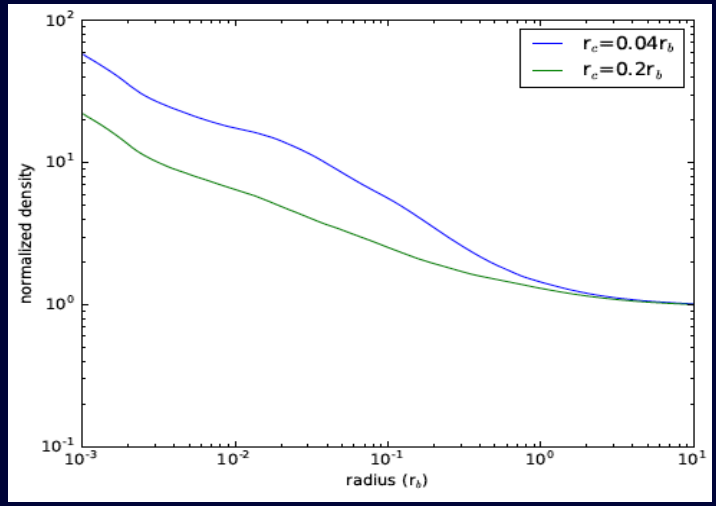

- First direct estimate of the centrifugal radius or **mean angular momentum** of the accretion flow.
- Outflow, **needed for the angular momentum loss**, flattens the radial density profile.

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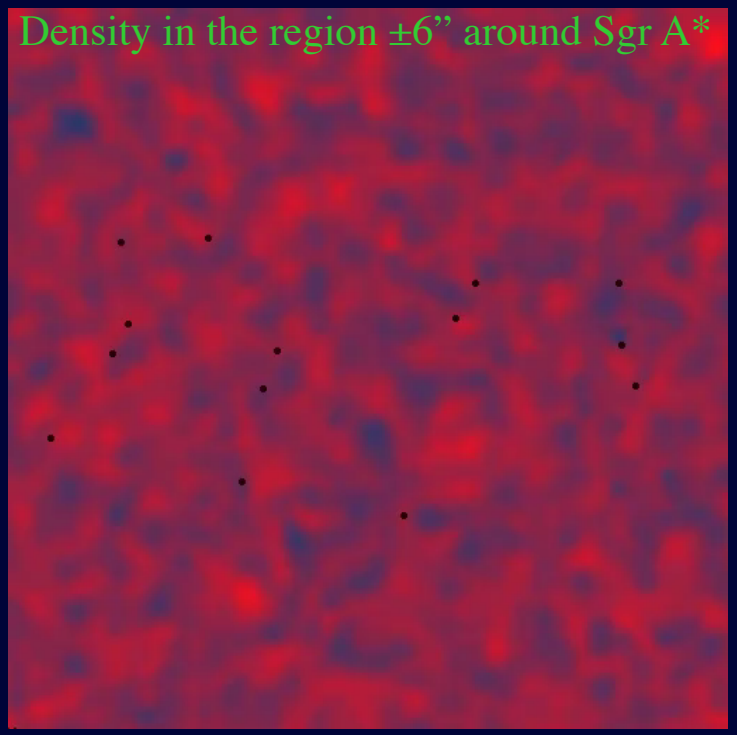
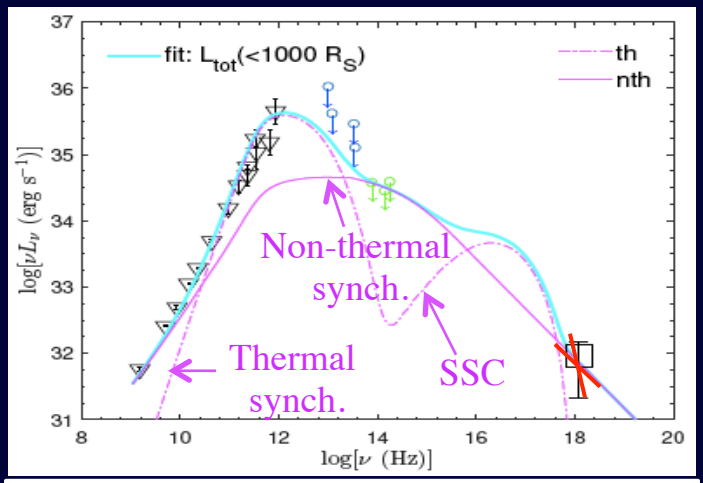


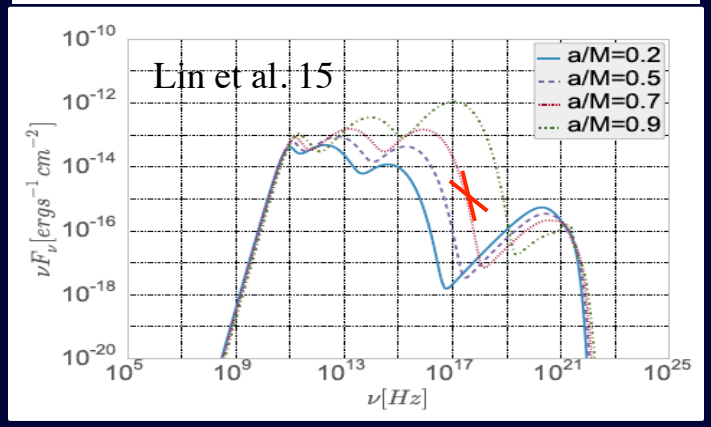
- Consistent with the values expected from the cluster wind.
- Expect significant change of the accretion rate with time

Russell, QDW, & Cuadra 16

Phenomena and physical processes in the innermost region

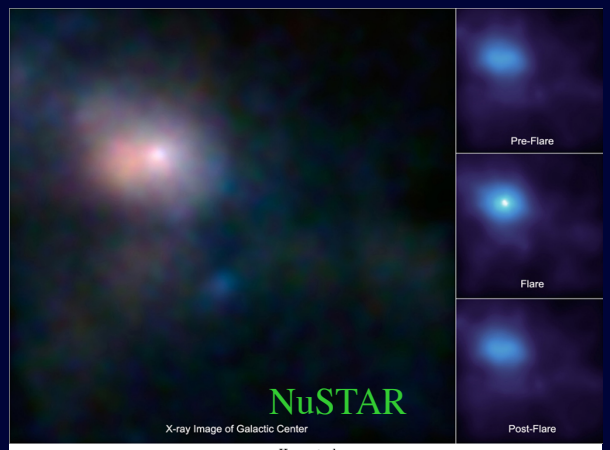
Quiescent point-like X-ray emission



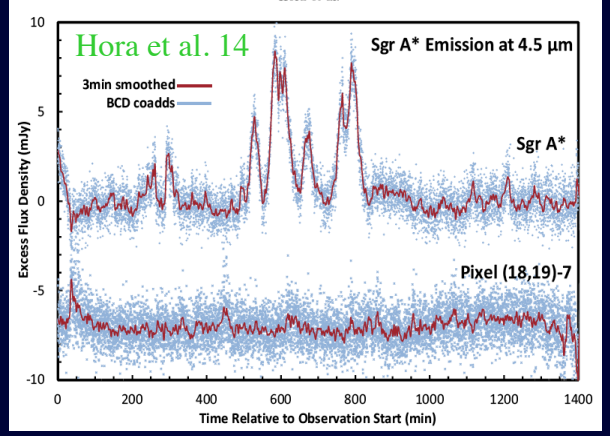


- Emission from r < a few x10^2 r_s -- the simulation inner boundary
- Account for ~ 4% of the observed counts
- Photon index Γ= 3.5-7.5
- Emission mechanisms:
  - ~~Bremsstrahlung~~
  - ~~Synchrotron~~
  - Synchrotron-self-Compton (SSC) + possible synchrotron from nonthermal electrons

X-ray and NIR flares of Sgr A*



Hora et al.



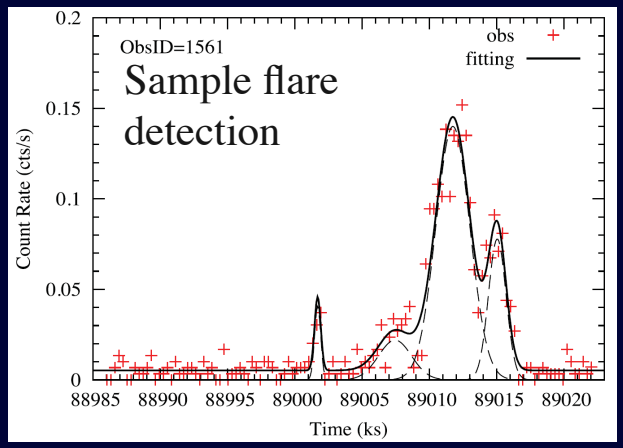
- ~ 100 flares in X-rays
  (from Chandra/XMM-Newton/Swift/NuSTAR)
- ~ 2 flares per day
- Duration $\tau \sim 1$ hour
- $L_X \sim 10^{33}$-10^{35} erg/s

Baganoff et al. 01; Ponti et al. 15; Yuan & Wang 16; Zhang et al. 17; Mossoux & Grosso 17

- A few times more frequent in NIR
- Polarized → synchrotron
- NIR flare region size < ~ 1 r_s
- Every X-ray flare has NIR counterpart, lasting longer, but not vice versa.

Genzel et al. 03; Dodds-Eden et al. 09; Hora et al. 14

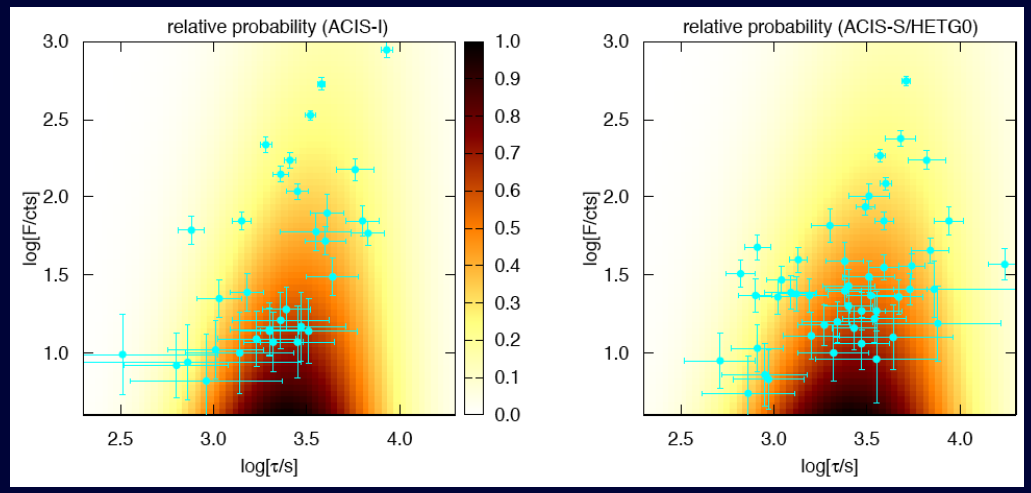
X-ray flare detection and statistics



- Maximum likelihood fitting
- Direct pileup correction
- Gaussian decomposition
- Parameter error measurement
- Detection incompleteness/bias correction

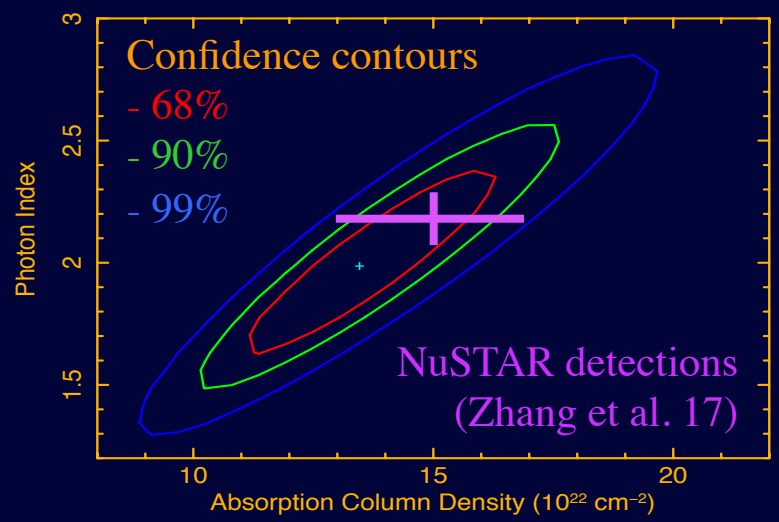
MCMC Bayesian analysis:

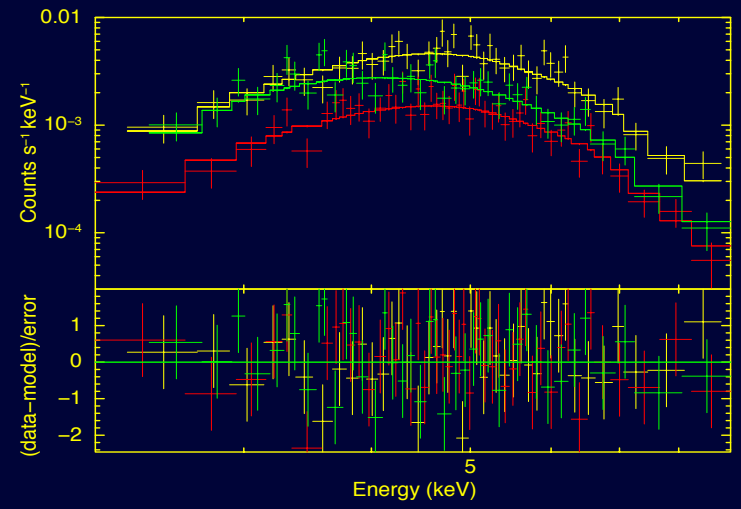
- $dN/dF \propto F^{-\alpha}$, α=1.7+-0.2
- $\tau \propto F^{-\beta}$, β=0.09+-0.16
- $\sigma(\log \tau)$ = 0.28+-0.07



Yuan & Wang 16; Yuan, QDW et al. 17

Spectral analysis of X-ray flares

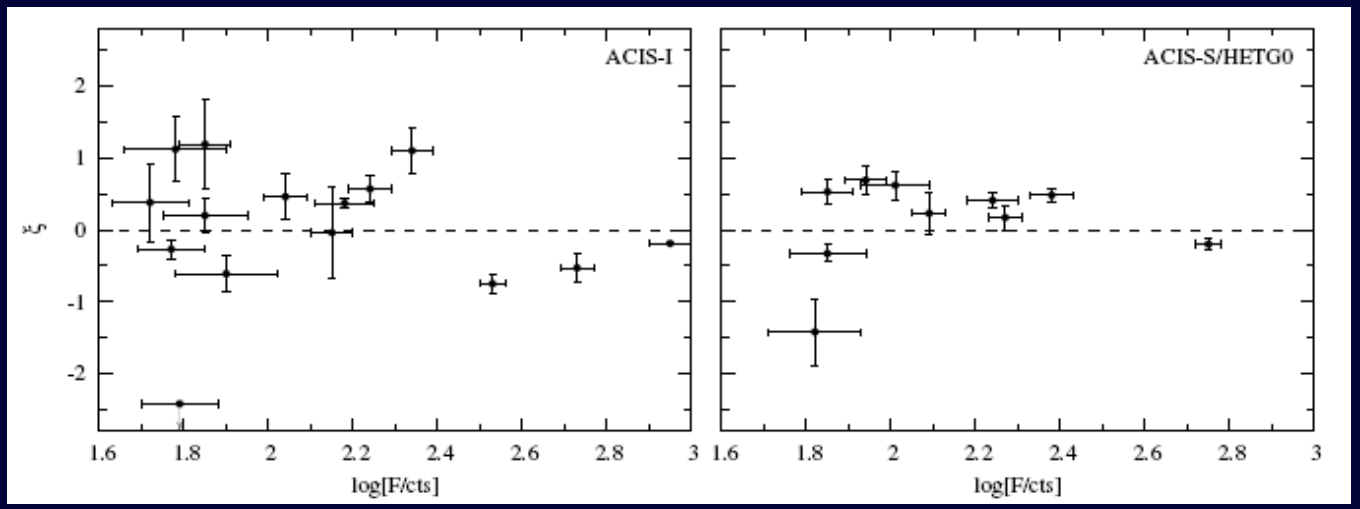




- Power law fit to the accumulated spectra of weak and strong fares
- Consistent single power law from NIR to hard X-ray
- No spectral dependence on flare brightness → single origin of the flares

Yuan, QDW et al. 17

Lightcurve asymmetry of X-ray flares

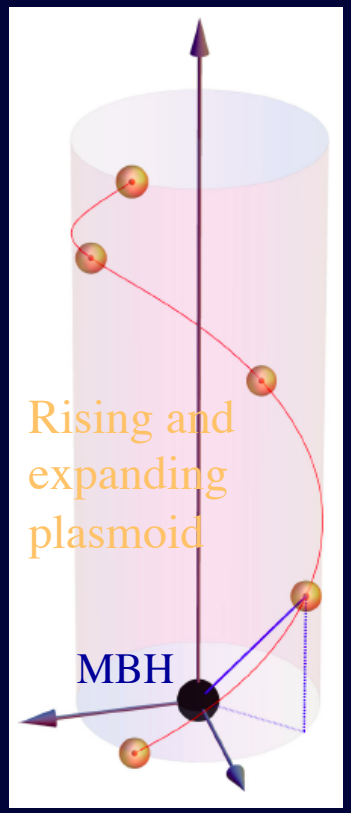


Fitting with the asymmetric Gaussian function for bright flares (# of counts > 50):

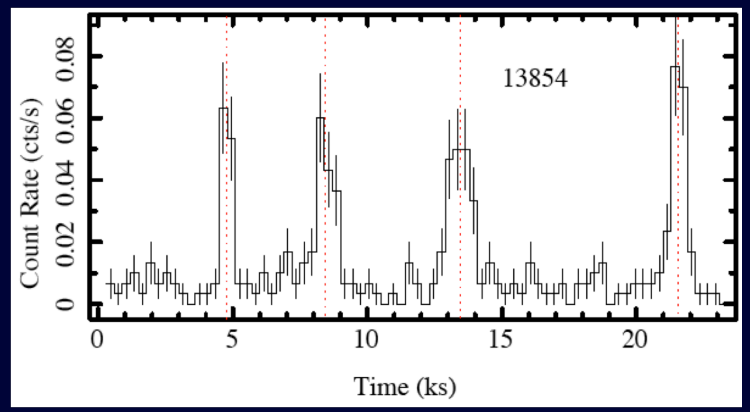
- ~ equal chance for $\xi > 0$ and $\xi < 0$
- No spectral difference between the rising and decaying phases

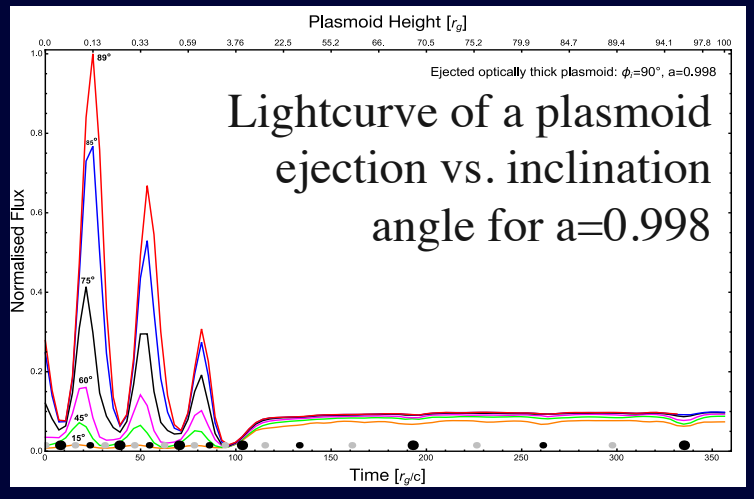
Yuan, QDW et al. 17

Relativistic effects & clustering properties

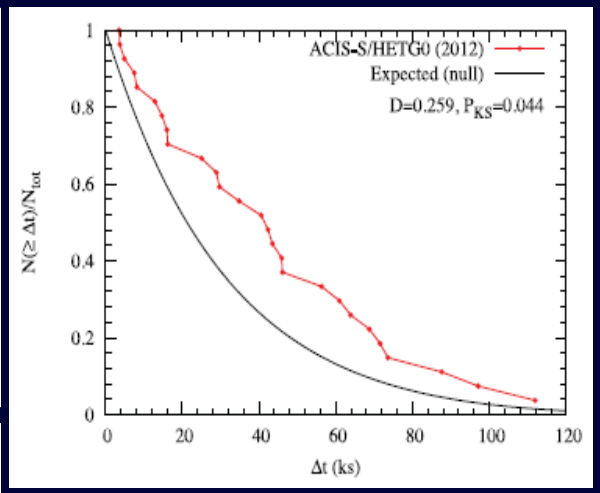


Younsi & Wu 15





Lightcurve of a plasmoid ejection vs. inclination angle for a=0.998



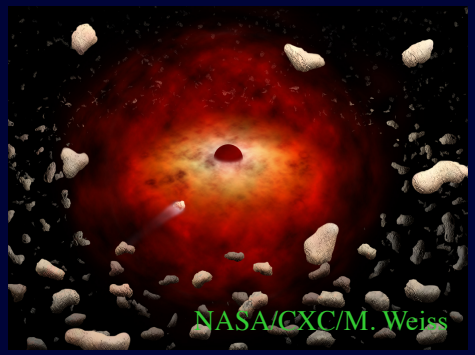
Detection of flare clustering on time scales of ~ 40 ks (>95% confidence)

Flare generation mechanisms

Magnetic reconnection

Differential rotation → magnetic stress and helicity in flux ropes → reach a threshold → fast reconnection → launch plasmoid and/or particle acceleration

Markoff et al. 01; Dodds-Eden et al. 10; Li et al. 17



Asteroid tidal disruption

Asteroids (sizes >10 km) approach ~1AU of the MBH → fragments → evaporation by friction; plasma instability → heat electrons to ~10^2 GeV

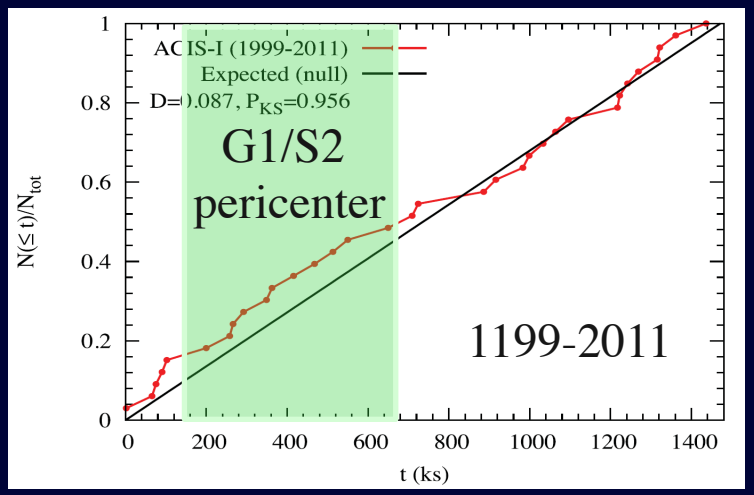
Cadez et al. 08; Kostic et al. 09; Zubovas et al. 12

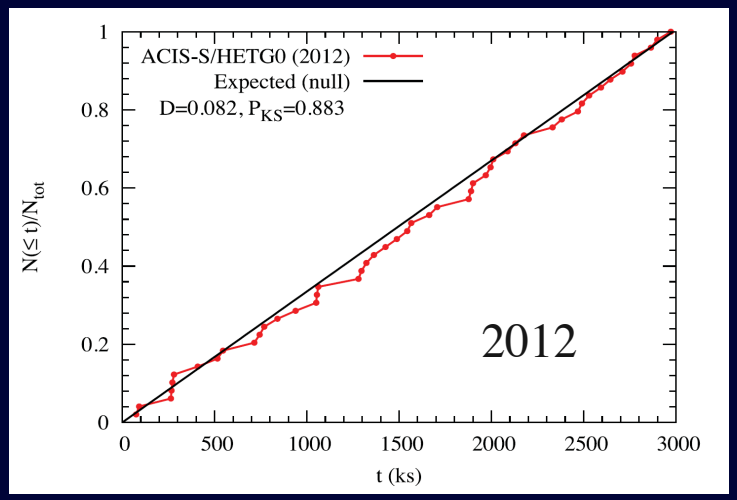
Preliminary test of the models

	Rate	dN/dF	τ vs. F	Cluster	Shape	Spectrum
Reconnection	√	×?	×?	√?	×?	?
Disruption	√	√	√	?	×?	?

- Magnetic reconnection may be described by the self-organized criticality (SOC) theory (Katz 1986; Bak et al. 1987), which predicts $\alpha \sim 1.5$ and $\beta \sim 0.5$ for spatial dimension $S = 3$.
- Tidal disruption of asteroids from a putative "Super-Oort cloud" around Sgr A* → $\alpha \sim 1.7$-2 and $\beta \sim 0$ (Zubovas et al. 12).
- Relativistic effects are likely important for the clustering and shape properties.
- Emission models are yet to be developed for the comparison.

Evolution of quiescent and flare emission

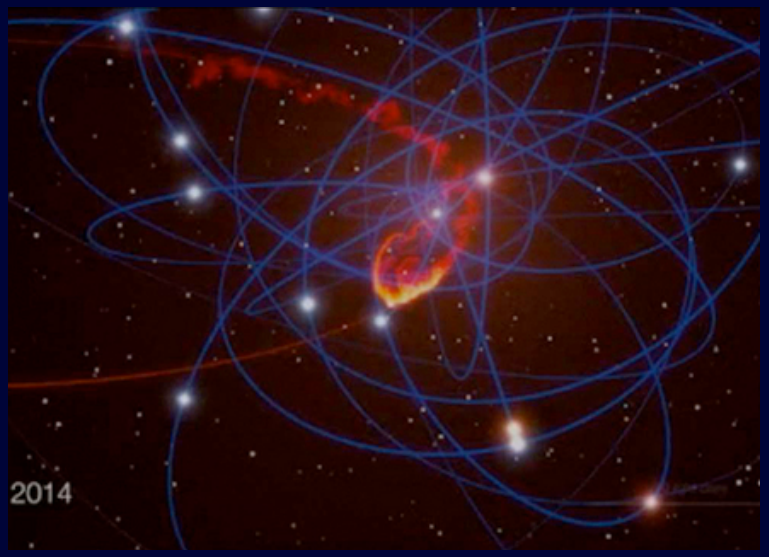


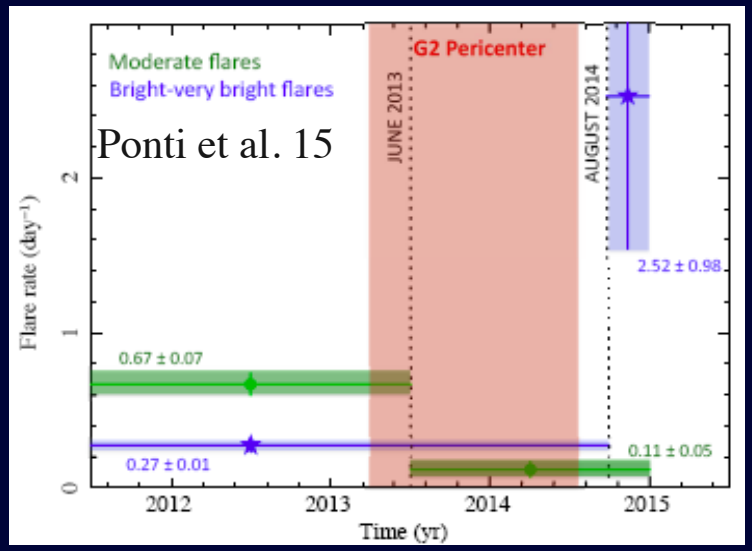


No significant change in the flare rate or quiescent emission from 1999-2012, even around/after G1/S2 passage

Yuan & Wang 16

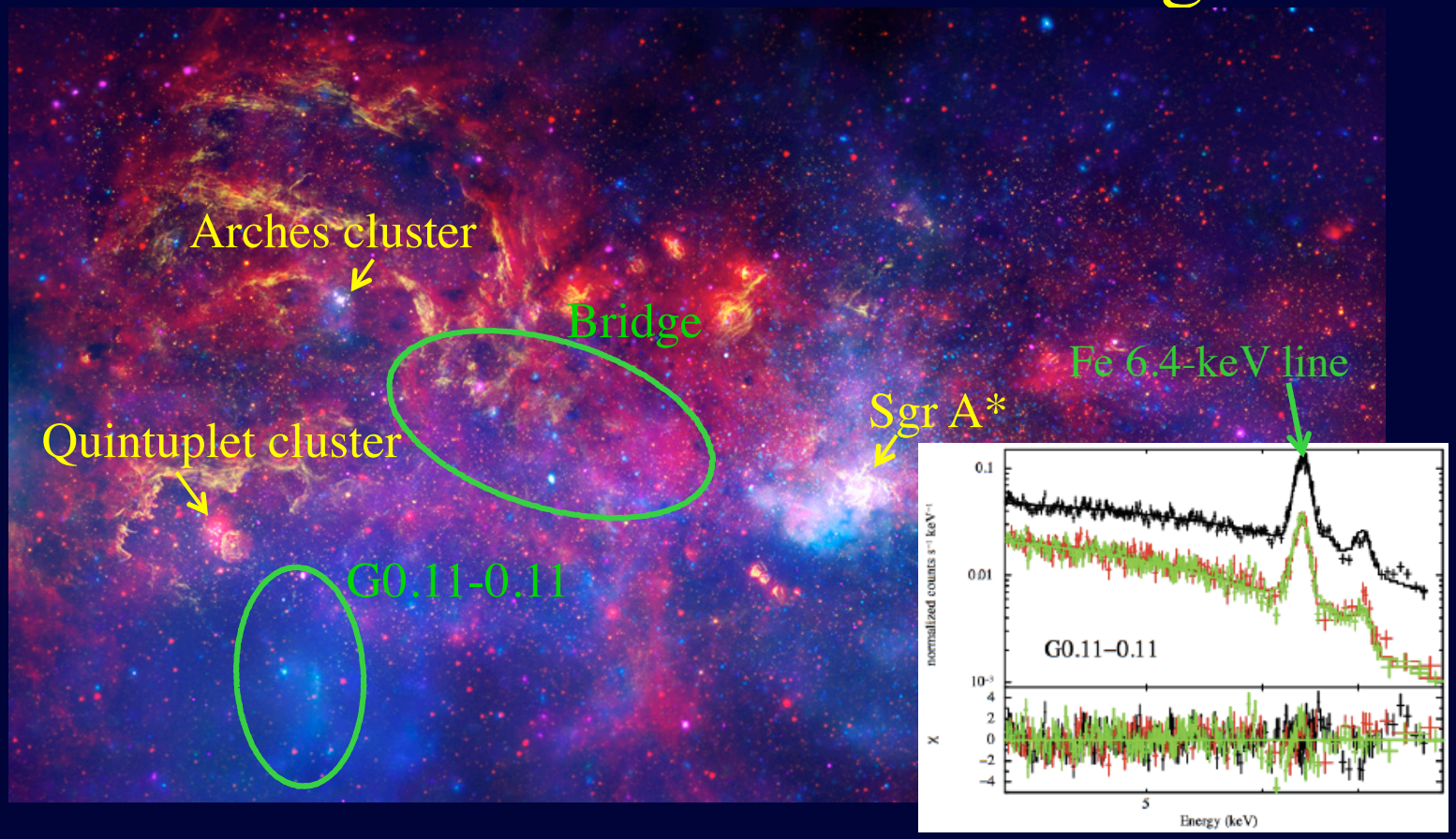
Recent G2 passage and X-ray flare rate



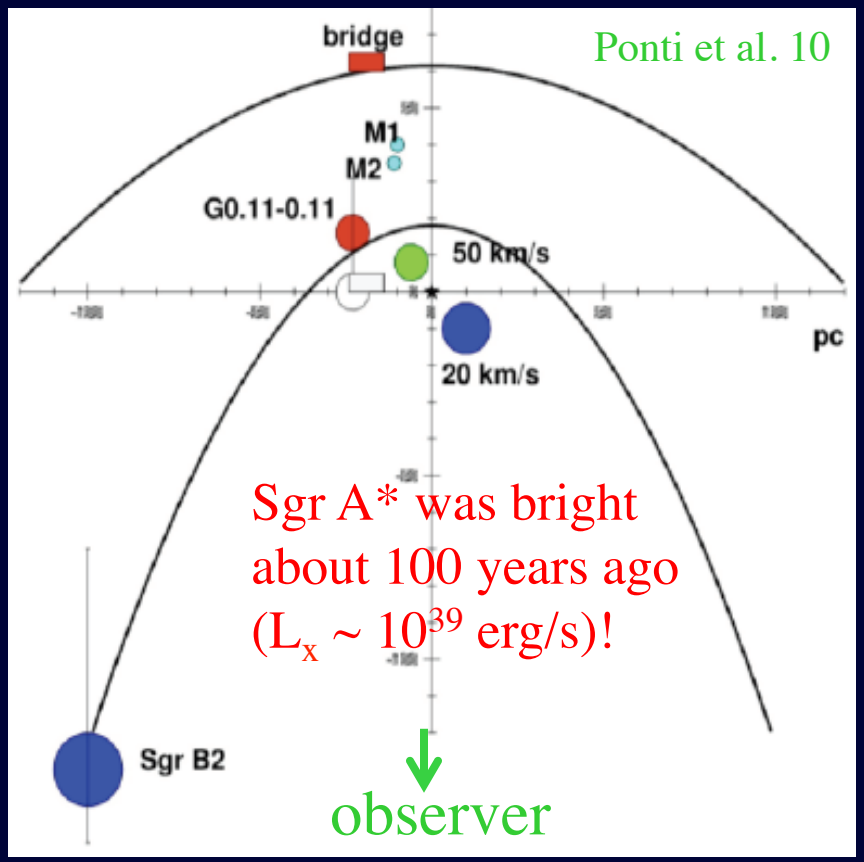


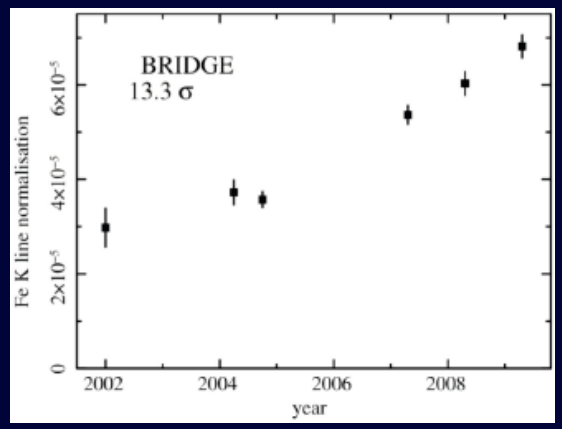
- In Spring 2014, G2 reached the pericenter at $1.5 \times 10^3\ r_s$.
- Faint flare rate decreased right before and after the passage (Mossoux & Grosso 17), while bright flare rate increased months later (Ponti et al.15), although their connection to G2 is not clear.

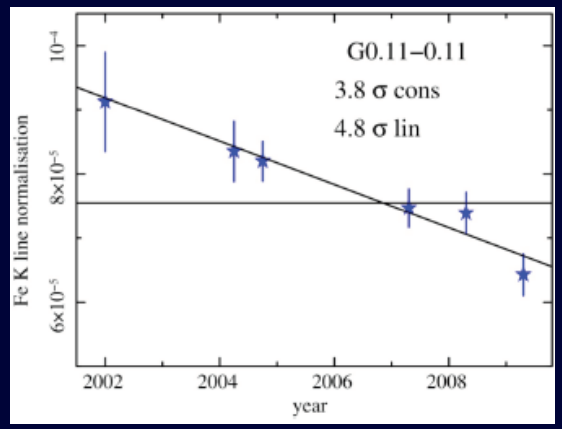
Evidence for recent bursts of Sgr A*



X-ray reverberation of bursts



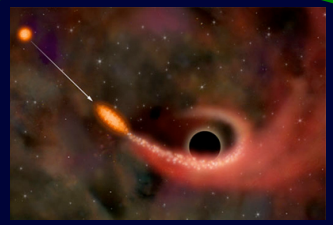




Life cycle of galactic nuclear activity

Cold gas accretion → SF & AGN → strong wind → blows out remaining cold gas shuts off cold accretion

Accretion from hot plasma → RIAF, emission mostly thermal at large radii, weak nonthermal near the MBH



Cycle interrupted by disruptions of asteroids/ planets/stars + perhaps dense clouds

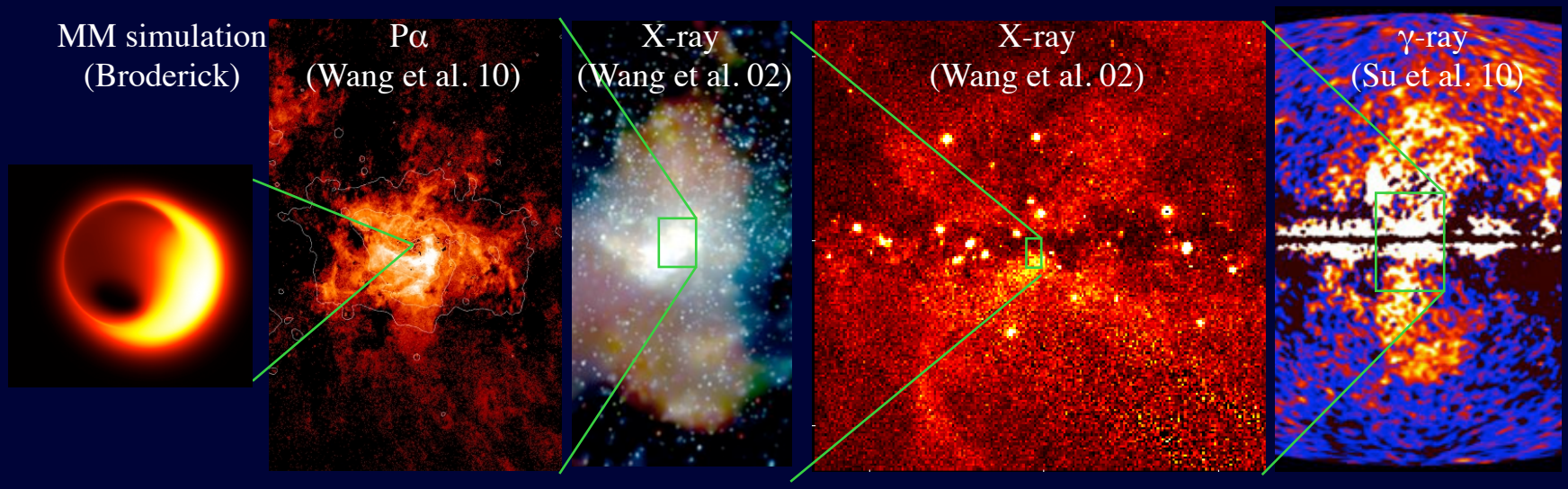
How energetic is the AGN outflow?

When the wind weakens

How energetic is the outflow of the RIAF?

From Sgr A* to Galactic ecosystem

- Better modeling + multi-wavelength observations from radio-X-ray → flare generation and emission mechanisms
- Structures over a 10^{10} scale range → history and energetics of Sgr A* episodes → effects on Galactic ecosystem



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Please come to my contributed talk: “X-ray Imaging and Spectroscopy of the Andromeda Galaxy's Nuclear Feedback”, 10:30AM this Thursday.