Statistical and theoretical studies of flares in Sgr A*

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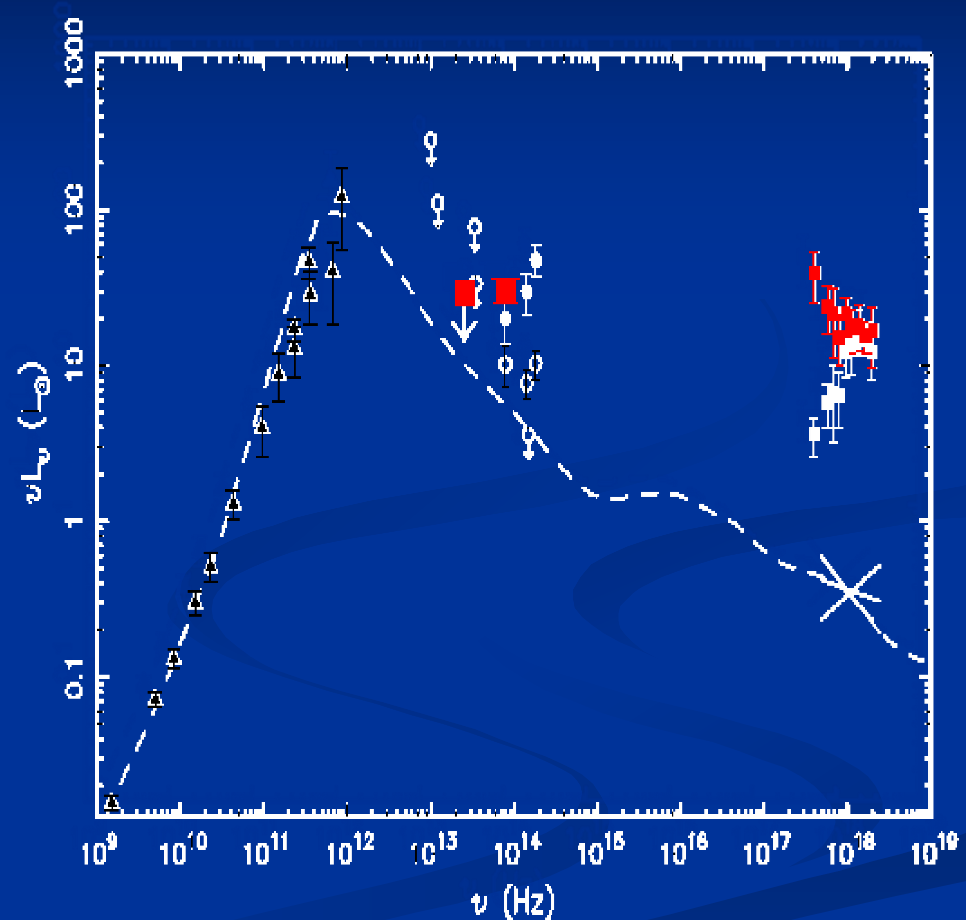
Black Hole Accretion and Jets, Oct. 21, 2016@ Kathmandu, Nepal

OUTLINE

- Flare observations for Sgr A*
- Statistical study of X-ray flares in Sgr A*
- Theoretical modeling of flares in Sgr A*
- Conclusion

Spectrum and Luminosity of Flares

- Quiescent state
  - $L_{bol} \sim 10^{36}$ erg/s
    $\sim 10^{-9}\ L_{Edd}$ for $M_{BH} = 4\times10^{6}$ M_{sun} ($\eta \sim 10^{-6}$);
  - RIAF works (Yuan et al. 2003)
- Flares state
  - Mainly at NIR and X-ray, also in radio and submm
  - brightest X-ray flares: 400x quiescent luminosity
- Spectrum of flares $(\nu L_\nu \sim \nu^{\alpha})$
  - NIR: $\alpha_{NIR} \sim 0.4$
  - X-ray: $\alpha_X \sim 0$

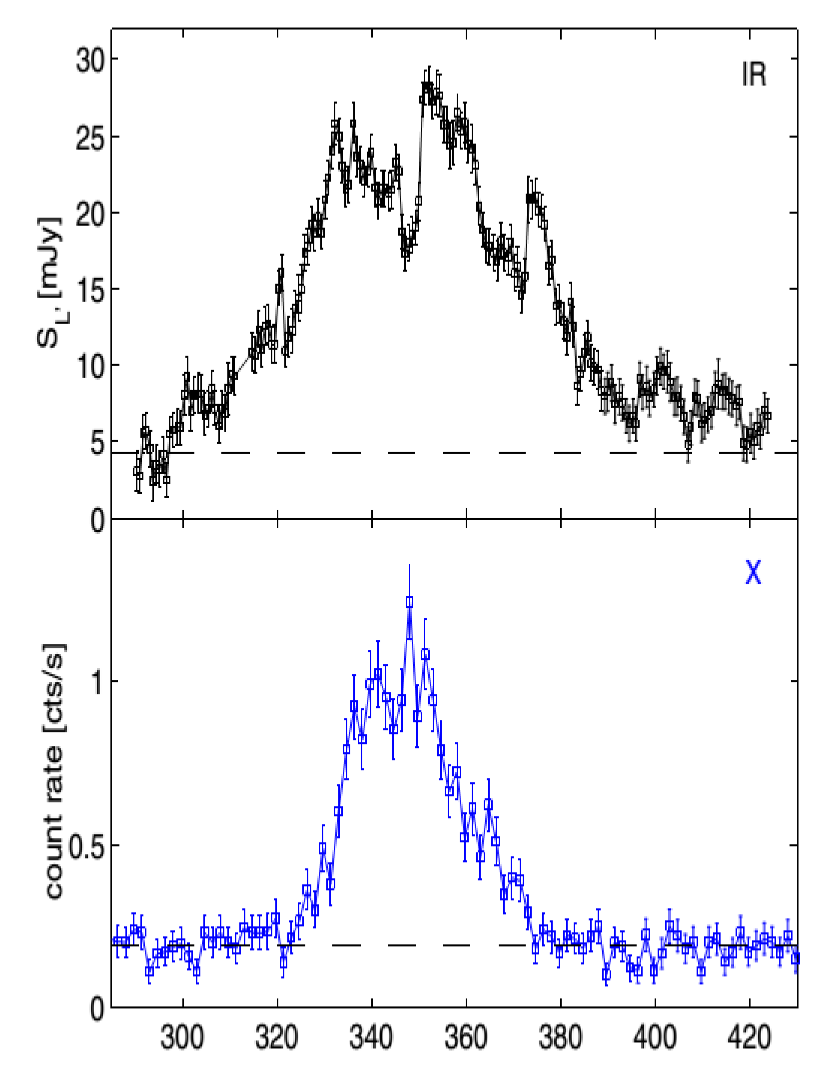


Hornstein et al. 2007;Porquet et al. 2003,2008;
Dodds-Eden et al. 2009; Nowark et al. 2012, Neilsen et al. 2013;…

Light Curves of Flares

Baganoff et al.2003;Eckart et al. 2006; Hornstein et al. 2007; Dodds-Eden et al 2009; Neilsen et al. 2013;…

- FWHM of NIR ~ 60 mins, X-ray ~ 30 mins
- substructrue in NIR but *not* in X-ray flares?
- X-ray and NIR flares occur simultaneously
- Occurrence rate:
  - IR/NIR : ~4 per day
  - X-ray : ~1 per day
  - every X-ray flare associated with the NIR flare, but *not* vice verse
- Flares also seen in mm, radio, but with smaller amplitudes, broader profiles (e.g., Yusef-Zadeh+06)



Proposed models for the flares

- Particle acceleration
  - magnetic reconnection (Yuan et al. 2004; Eckart et al. 2006; Dodds-Eden et al. 2009)
  - shock (Markoff et al. 2001)
- Dynamical models
  - Accretion instability (Tagger & Melia 2006; Falanga et al. 2008)
  - Orbiting hot spot (e.g., Broderick & Loeb 2005; Hamaus et al. 2009)
  - *Expanding plasma blob* (Yusef-Zadeh et al. 2006, Eckart et al. 2006, Dodds-Eden et al. 2010; Kusunose & Takahara 2011;Trap et al. 2011)
  - Tidal disruption of asteroids (Cadez et al. 2008; Kostic et al. 2009; Zubovas et al. 2012)

Almost all of these works are **phenomenological**.

Statistical study of the X-ray flares in Sgr A*

Methodology

Assuming a flare distribution, described by $r, \alpha_E, \kappa, \alpha_{ET}, A$

$$dN/dE \propto \begin{cases} E^{-\alpha_E}, & E_{min} \le E \le E_{max} \\ 0, & \text{otherwise} \end{cases},$$

$$\log \sigma_i = \log A + \alpha_{ET} \log(E_i/100)$$

Synthetic Light Curve, Calculate structure function and count rate distribution

$$R(t) = \sum_{i=1}^{[\kappa]} \frac{E_i}{\sqrt{2\pi}\sigma_i} \exp\left[-\frac{1}{2}\left(\frac{t-\mu_i}{\sigma_i}\right)^2\right] + r$$

χ^2 statistics comparison: judge the best model

No

Yes

Output the flare distribution

$$\chi^2 = \chi^2_{CR} + \chi^2_{SF}$$

$$\chi^2_{SF} = (\log \mathbf{V}_{obs} - \log \mathbf{V}_{sim})^T \mathbf{C}_{SF}^{-1} (\log \mathbf{V}_{obs} - \log \mathbf{V}_{sim})$$

$$\chi^2_{CR} = (\mathbf{n}_{obs} - \mathbf{n}_{sim})^T \mathbf{C}^{-1} (\mathbf{n}_{obs} - \mathbf{n}_{sim})$$

MCMC fitting:

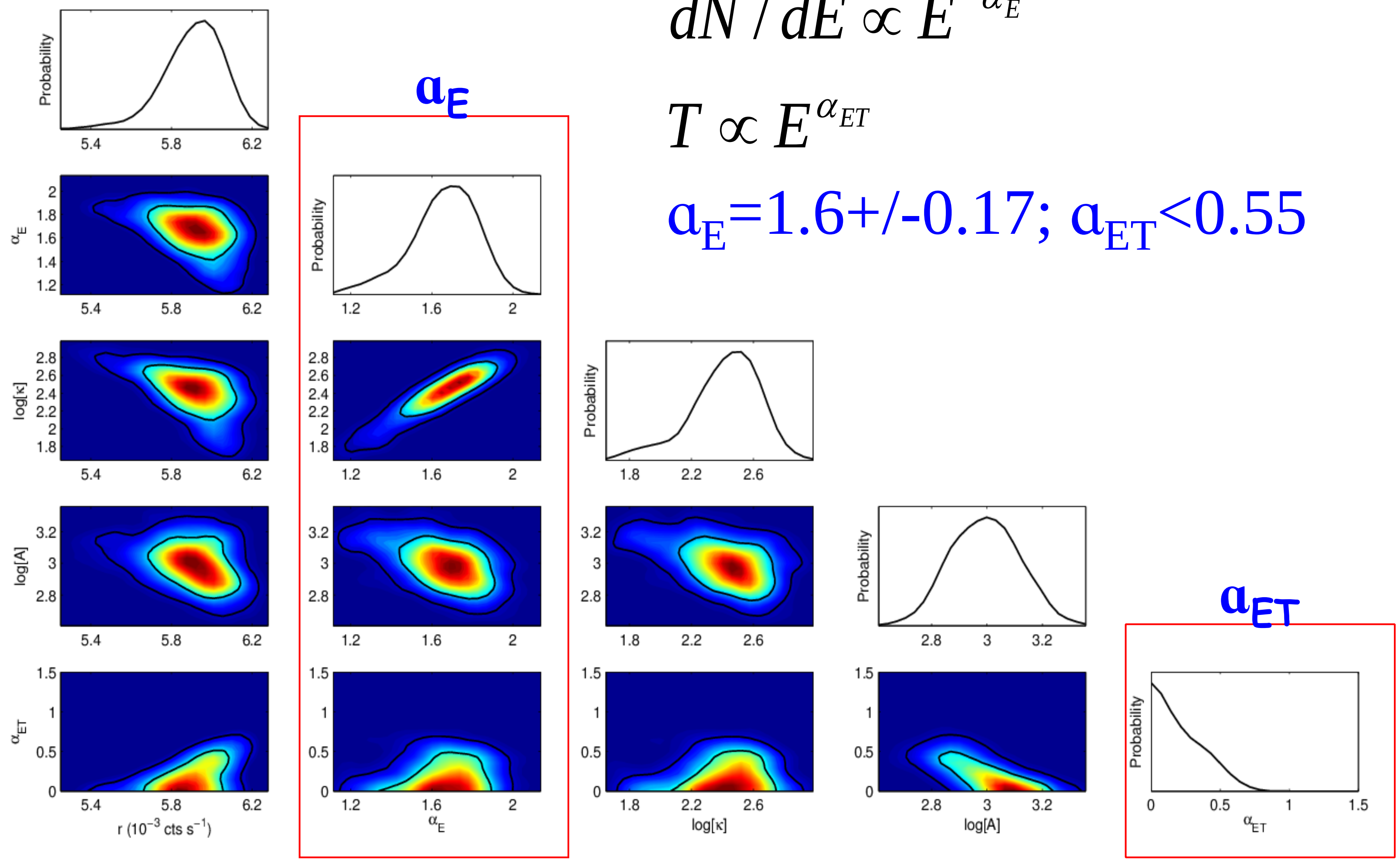
Power-law distributions for flare fluence and fluence-duration correlation

Li et al. 2015b

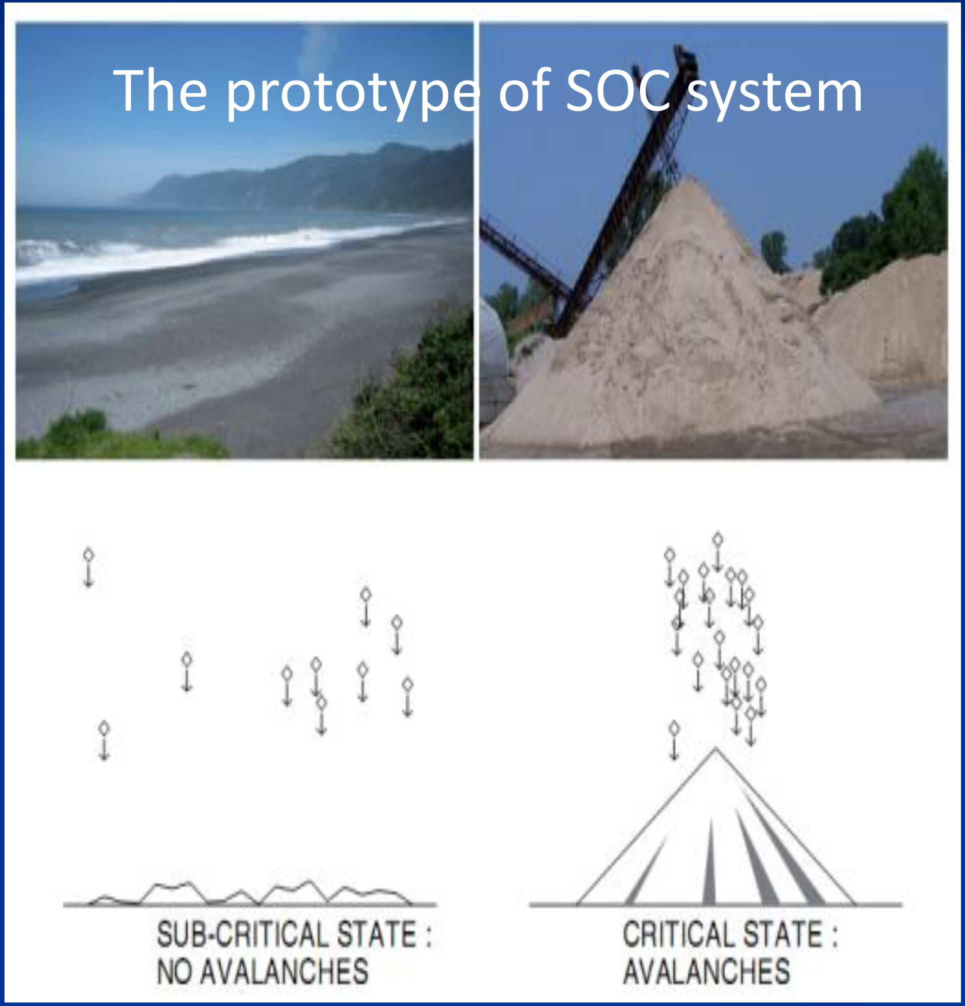
$$dN/dE \propto E^{-\alpha_E}$$

$$T \propto E^{\alpha_{ET}}$$

α_E=1.6+/-0.17; α_{ET}<0.55



Self-Organized Criticality (SOC): statistical approach

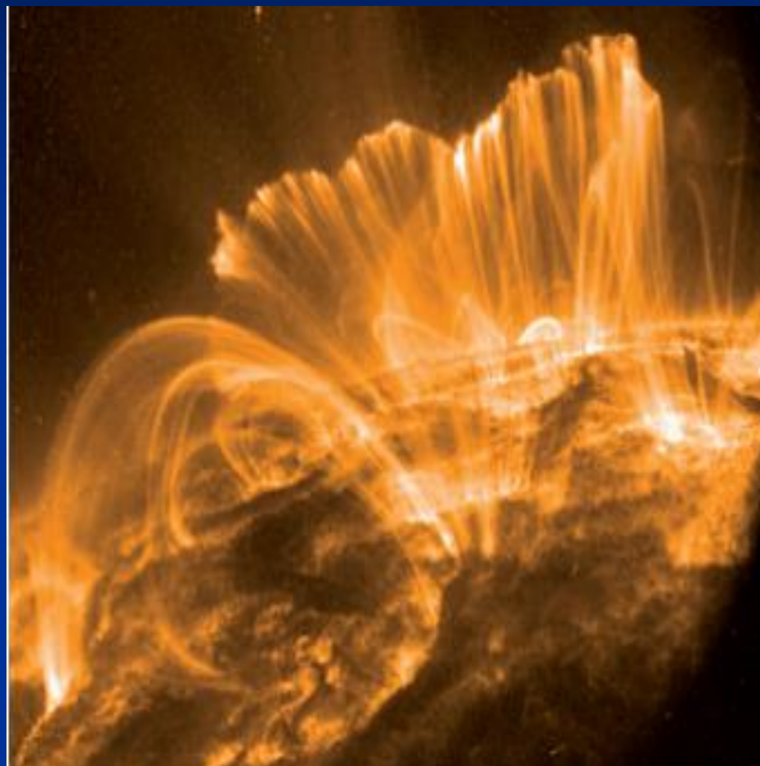


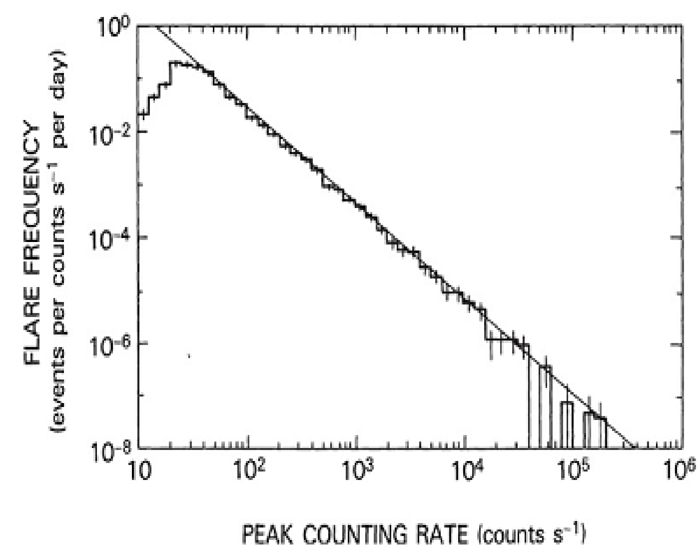
SOC:
A class of dynamical system with nonlinear energy dissipation that is slowly and continuously driven toward a critical value of an instability threshold.

Consequences:
Power-law distributions of various event parameters, such as peak energy, total energy (fluence) and durations.

Solar flares:

Statistics results and Self-Organized Criticality (SOC)





Peak count rate distribution($N \geq 6000$) with $h\nu \gtrsim 25$ keV, described by a power law with a slope of $\alpha_P = -1.8$ over 4 orders of magnitude (Dennis 1985).

- power-law distributions also observed in flare duration, total energy and flux.
- $\alpha_P = -1.8$, consistent with an S=3 SOC system driven by magnetic reconnection in the solar atmosphere.
- power-law index can be used to diagnose the dimensionality (S) of the process leading to flares, and further their physical mechanism;

Confrontation with SOC theory

Simulation Results:

- power-law distributions of fluence and width-fluence correlation;

Fractal-diffusive SOC theory:

- power-law indexes depend on the dimension S;
- For S=3 (β~1.0, D_S~(S+1) /2)

BEST-FIT MODEL PARAMETERS WITH THE MCMC METHOD

r (10^{-3} cts s^{-1})	$\alpha_{\rm E}$	$\log(\kappa)$	$\log(A)$	$\alpha_{\rm ET}$	χ^2_ν
5.90 ± 0.14	1.65 ± 0.17	2.41 ± 0.22	2.99 ± 0.12	< 0.55	0.9

$$\alpha_{\rm E}^{\rm th} = 1 + \frac{S-1}{D_{\rm S} + 2/\beta} \approx 1.5$$

$$\alpha_{\rm ET}^{\rm th} = \frac{2}{D_{\rm S}\beta + 2} \approx 0.5$$

S=3 for X-ray flares from Sgr A*

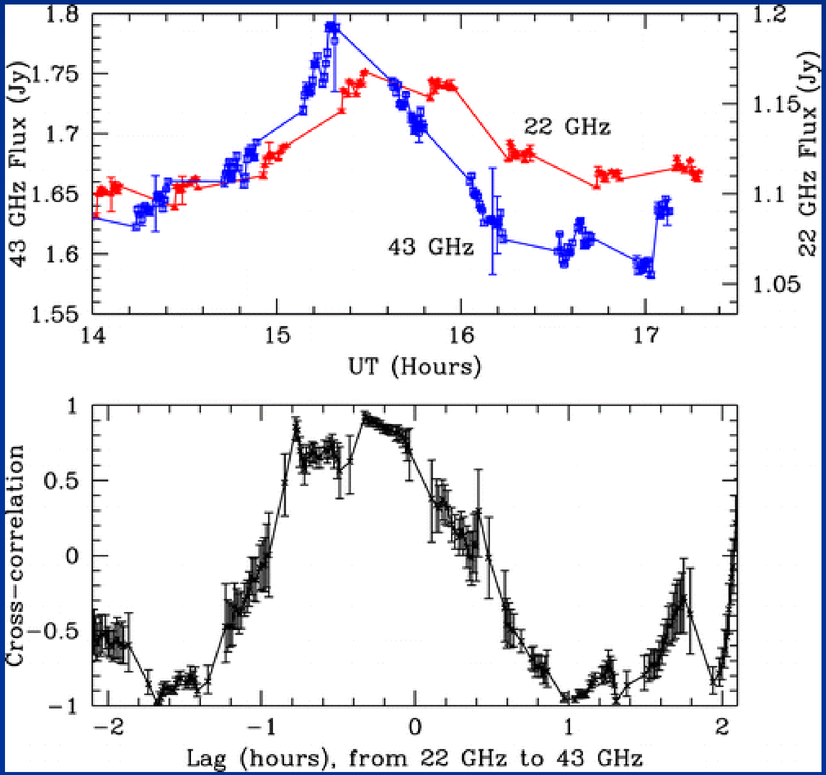
Implications on the nature of X-ray flares of Sgr A*

- Statistical properties of Sgr A* are well consistent with S=3 fractal-diffusive SOC theory, same as solar flares
- Two Implications:
  - Flares in Sgr A* originate from reconnection
  - in the surface of accretion flow, not in the jet
- This is also supported by:
  - Flares are associated ejection of blobs (Yusef-Zadeh et al. 2006), which is caused by reconnection (second part of this talk)

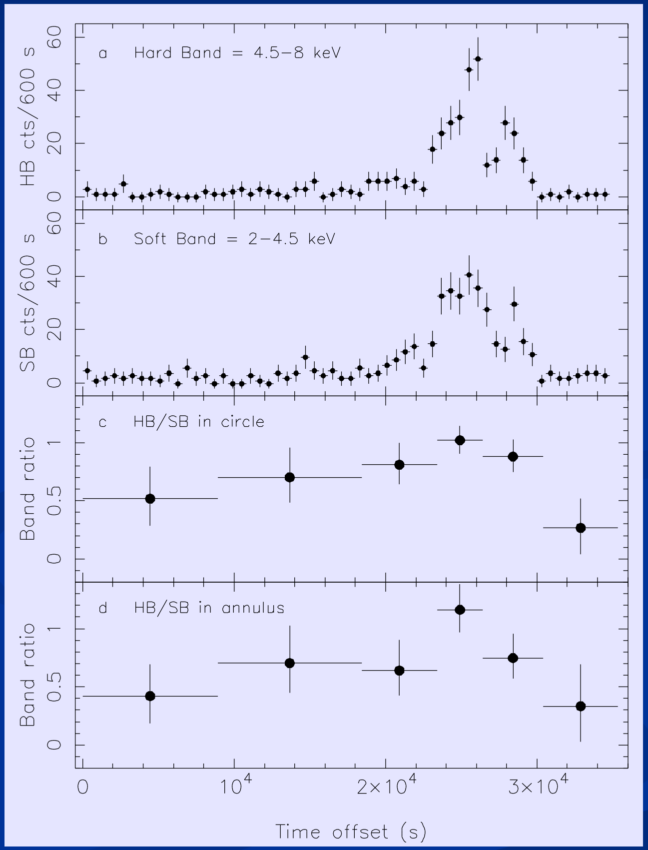
Theoretical model for the flares in Sgr A*

Time lag as evidence for episodic ejection of radio blobs

Yusef-Zadeh+2006,2008; Brinkerink+2015;……



Radio light curves and cross correlation



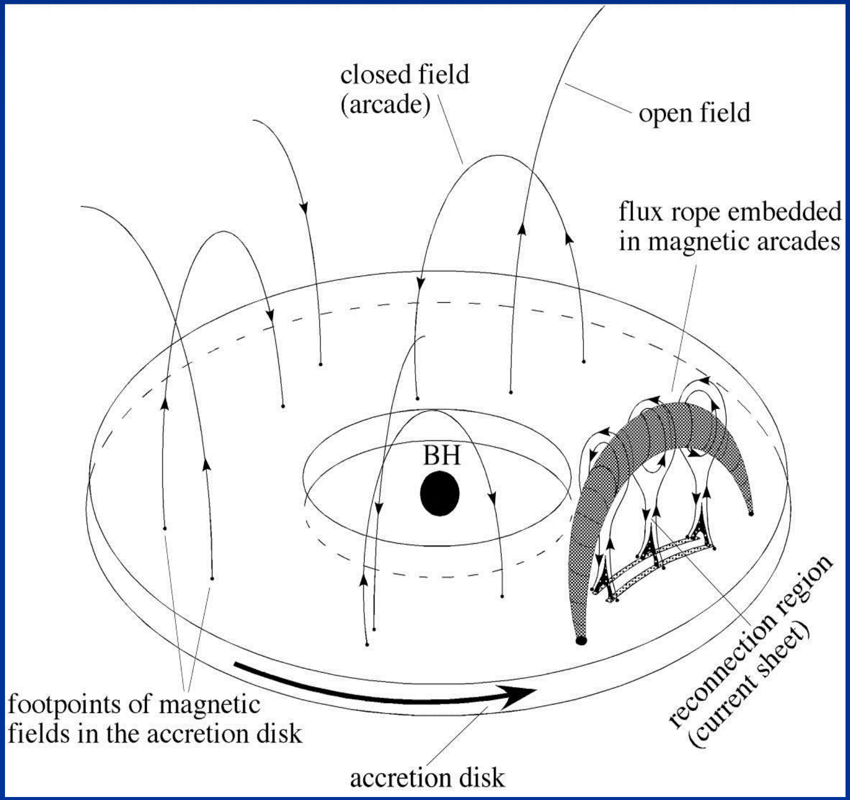
X-ray flare

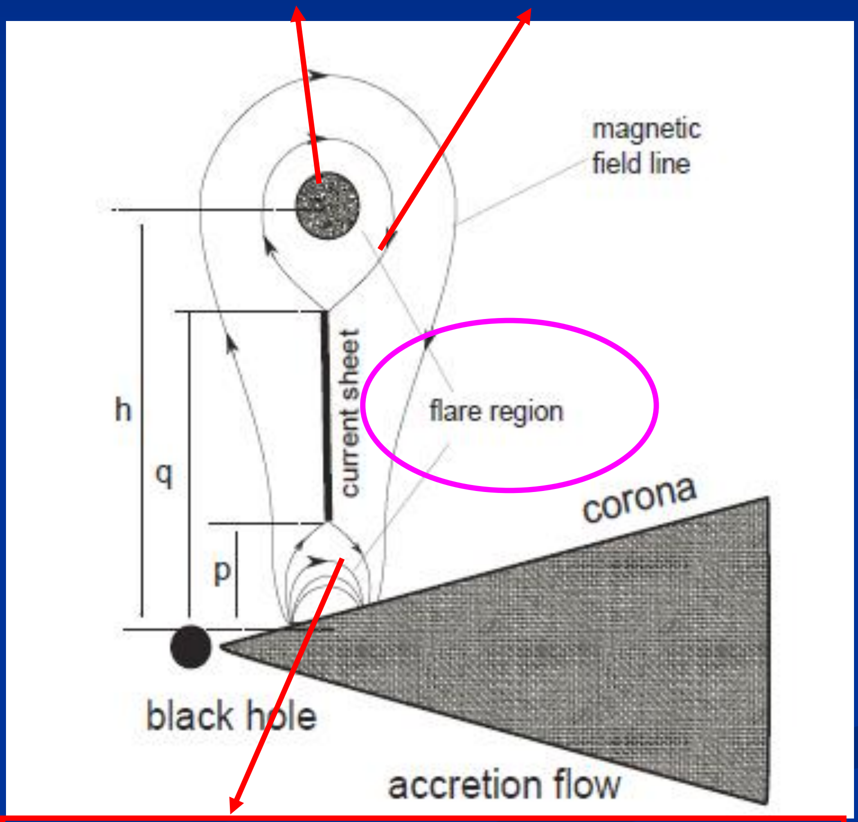
associated with X-ray, IR & radio flares

Model for flare & ejection of blobs

Yuan et al. 2009

a) radio & submm flares? also IR & X-ray?
b) Time lags between different wavelengths





By analogy with coronal mass ejections (CMEs)/solar flares

synchrotron of electrons accelerated
by reconnection:
IR & X-ray flares?

Equations for Dynamical Evolutions of Blobs

$$\left\{\begin{aligned}
\gamma_{\rm b}^3\frac{d^2h}{dt^2} &= \frac{{B_0}^2\lambda^4}{8hmL_{\rm PQ}^2}\left[\frac{H_{\rm PQ}^2}{2h^2}-\frac{(p^2+\lambda^2)(h^2-q^2)}{h^2+\lambda^2}\right.\\
&\quad\left.-\frac{(q^2+\lambda^2)(h^2-p^2)}{h^2+\lambda^2}\right]-\frac{GM_\bullet\gamma_{\rm b}}{(R_0+h)^2}.\\
\frac{dm}{dt} &= B_0M_{\rm A}\sqrt{\frac{n_{\rm e}m_{\rm H}}{\pi}}\frac{\lambda^2(q-p)(h^2+\lambda^2)}{(h^2-y_0^2)(y_0^2+\lambda^2)}\\
&\quad\times\sqrt{\frac{f(y_0)(q^2-y_0^2)(y_0^2-p^2)}{(p^2+\lambda^2)(q^2+\lambda^2)}},\\
\frac{dp}{dt} &= p'\dot{h},\\
\frac{dq}{dt} &= q'\dot{h}.
\end{aligned}\right.$$

with

$$p' = \frac{\tilde{A}_{\rm 0h}A_{\rm Rq}-A_{\rm Rh}A_{\rm 0q}}{A_{\rm Rp}A_{\rm 0q}-A_{\rm 0p}A_{\rm Rq}},$$

$$q' = \frac{A_{\rm Rh}A_{\rm 0p}-\tilde{A}_{\rm 0h}A_{\rm Rp}}{A_{\rm Rp}A_{\rm 0q}-A_{\rm 0p}A_{\rm Rq}},$$

$$\tilde{A}_{\rm 0h} = \frac{cE_z}{B_0\lambda\dot{h}}+A_{\rm 0h} = \frac{M_{\rm A}V_{\rm A}B_y(0,y_0)}{B_0\lambda\dot{h}}+A_{\rm 0h},$$

Determining the evolution profiles of p, q, h, m

Equations Cont'd

$$
\begin{aligned}
A_{\mathrm{R}} = {} & \frac{\lambda H_{\mathrm{PQ}}}{2hL_{\mathrm{PQ}}} \ln\left[\frac{\lambda H_{\mathrm{PQ}}^3}{r_{00}L_{\mathrm{PQ}}(h^4-p^2q^2)}\right] \\
& + \tan^{-1}\left(\frac{\lambda}{h}\sqrt{\frac{p^2+\lambda^2}{q^2+\lambda^2}}\sqrt{\frac{h^2-q^2}{h^2-p^2}}\right) \\
& + \frac{\lambda}{qL_{\mathrm{PQ}}}\left\{(h^2-q^2)F\left[\sin^{-1}\left(\frac{q}{h}\right),\frac{p}{q}\right]\right. \\
& + (q^2-p^2)\Pi\left[\sin^{-1}\left(\frac{q}{h}\right),\frac{p^2+\lambda^2}{q^2+\lambda^2},\frac{p}{q}\right] \\
& \left. - \frac{H_{\mathrm{PQ}}^2}{h^2}\Pi\left[\sin^{-1}\left(\frac{q}{h}\right),\frac{p^2}{h^2},\frac{p}{q}\right]\right\} \\
= {} & \frac{\pi}{4} + \ln\left(\frac{2\lambda}{r_{00}}\right),
\end{aligned}
$$

$$
\begin{aligned}
A_{\mathrm{Rp}} = {} & \frac{\lambda p(h^2+\lambda^2)}{q(p^2+\lambda^2)^2}\sqrt{\frac{p^2+\lambda^2}{q^2+\lambda^2}}\left\langle\left(1-\frac{q^2}{h^2}\right)\right. \\
& \times \Pi\left[\sin^{-1}\left(\frac{q}{h}\right),\frac{p^2}{h^2},\frac{p}{q}\right] \\
& - F\left[\sin^{-1}\left(\frac{q}{h}\right),\frac{p}{q}\right] \\
& \left. - \frac{q}{2h}\sqrt{\frac{h^2-q^2}{h^2-p^2}}\left\{1+\ln\left[\frac{\lambda H_{\mathrm{PQ}}^3}{r_{00}L_{\mathrm{PQ}}(h^4-p^2q^2)}\right]\right\}\right\rangle,
\end{aligned}
$$

$$
\begin{aligned}
A_{\mathrm{Rq}} = {} & \frac{\lambda(h^2+\lambda^2)}{(q^2+\lambda^2)^2}\sqrt{\frac{q^2+\lambda^2}{p^2+\lambda^2}}\left\langle\left(1-\frac{p^2}{h^2}\right)\right. \\
& \times \Pi\left[\sin^{-1}\left(\frac{q}{h}\right),\frac{p^2}{h^2},\frac{p}{q}\right] \\
& - F\left[\sin^{-1}\left(\frac{q}{h}\right),\frac{p}{q}\right] \\
& \left. - \frac{q}{2h}\sqrt{\frac{h^2-p^2}{h^2-q^2}}\left\{1+\ln\left[\frac{\lambda H_{\mathrm{PQ}}^3}{r_{00}L_{\mathrm{PQ}}(h^4-p^2q^2)}\right]\right\}\right\rangle,
\end{aligned}
$$

$$
\begin{aligned}
A_{\mathrm{Rh}} = {} & \frac{\lambda}{2h^2L_{\mathrm{PQ}}H_{\mathrm{PQ}}}\left\{2\frac{h^6-\lambda^2p^2q^2}{h^2+\lambda^2}\right. \\
& - \frac{h^2(p^2+q^2)(h^2-\lambda^2)}{h^2+\lambda^2} \\
& \left. + (h^4-p^2q^2)\ln\left[\frac{\lambda H_{\mathrm{PQ}}^3}{r_{00}L_{\mathrm{PQ}}(h^4-p^2q^2)}\right]\right\} \\
& + \frac{\lambda}{hqL_{\mathrm{PQ}}}\left\{(h^2+q^2)F\left[\sin^{-1}\left(\frac{q}{h}\right),\frac{p}{q}\right]\right. \\
& - q^2E\left[\sin^{-1}\left(\frac{q}{h}\right),\frac{p}{q}\right] \\
& \left. - \frac{h^4-p^2q^2}{h^2}\Pi\left[\sin^{-1}\left(\frac{q}{h}\right),\frac{p^2}{h^2},\frac{p}{q}\right]\right\}.
\end{aligned}
$$

$$
\begin{aligned}
A_0^0 = {} & \frac{2I_0}{c}\frac{\lambda}{qL_{\mathrm{PQ}}}\left[(h^2-q^2)K\left(\frac{p}{q}\right) + (q^2-p^2)\right. \\
& \left. \times \Pi\left(\frac{p^2+\lambda^2}{q^2+\lambda^2},\frac{p}{q}\right) - \frac{H_{\mathrm{PQ}}^2}{h^2}\Pi\left(\frac{p^2}{h^2},\frac{p}{q}\right)\right],
\end{aligned}
$$

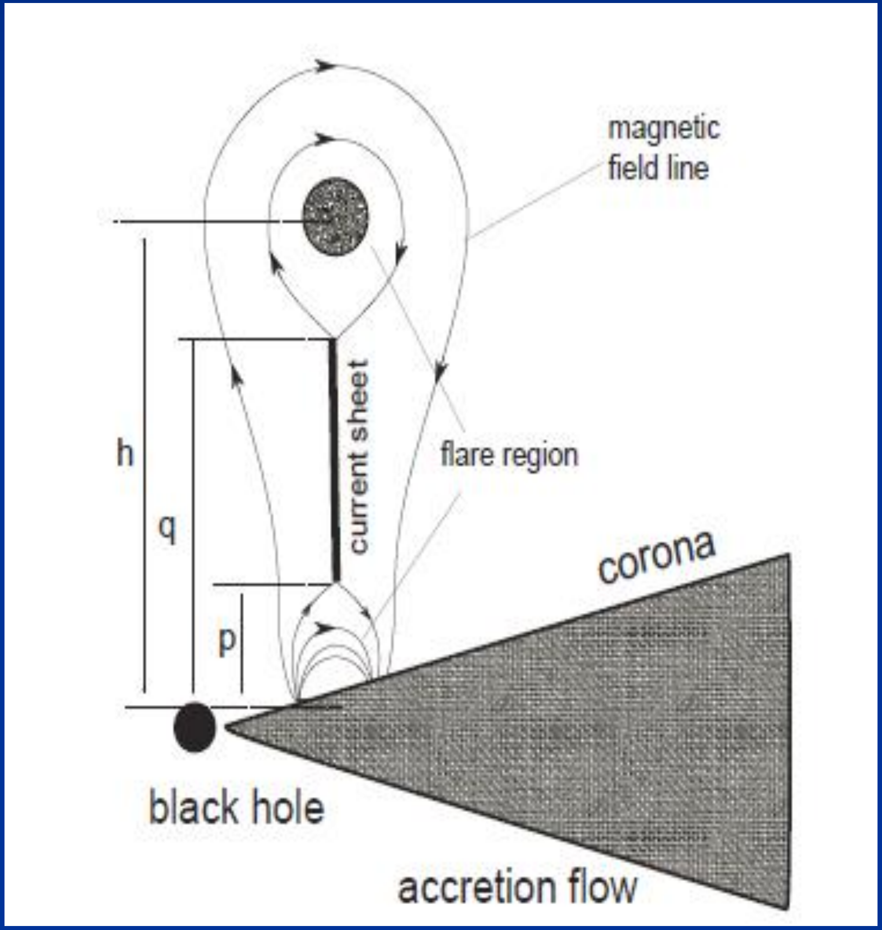
$$
\begin{aligned}
A_{0\mathrm{p}} = {} & \frac{\lambda p(h^2+\lambda^2)(q^2+\lambda^2)}{h^2q[(p^2+\lambda^2)(q^2+\lambda^2)]^{3/2}} \\
& \times\left[(h^2-p^2)\Pi\left(\frac{p^2}{h^2},\frac{p}{q}\right) - h^2K\left(\frac{p}{q}\right)\right],
\end{aligned}
$$

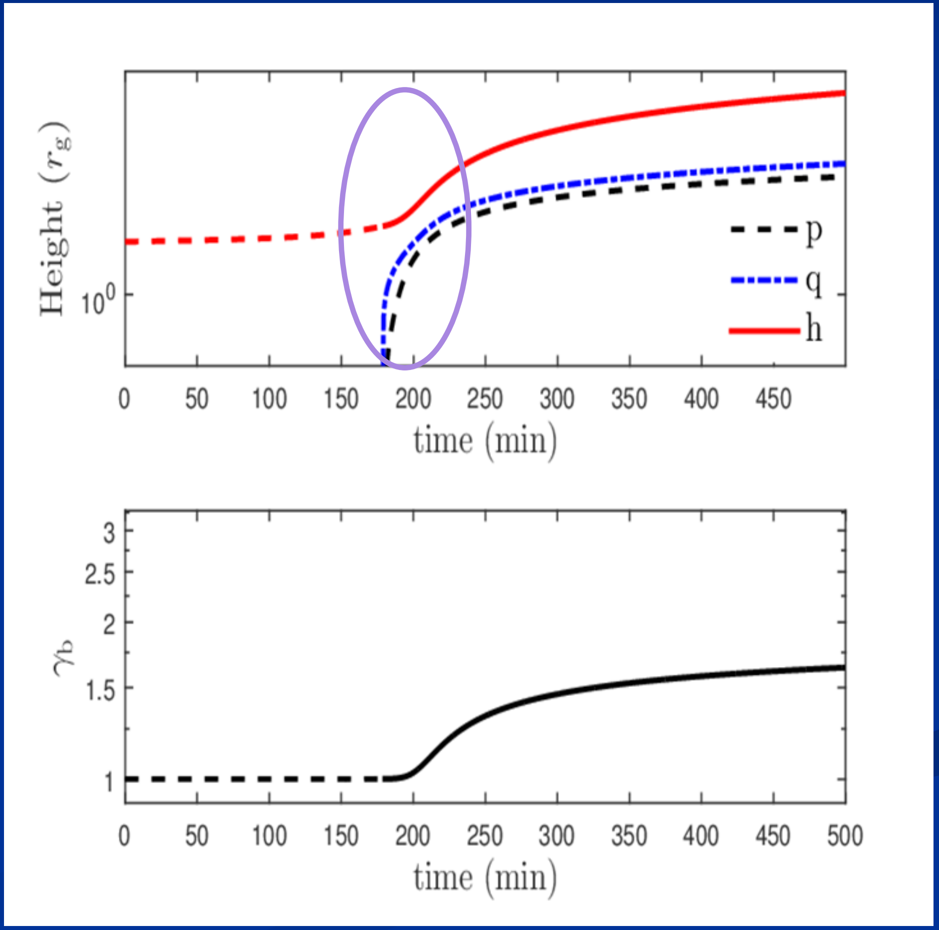
$$
\begin{aligned}
A_{0\mathrm{q}} = {} & \frac{\lambda(h^2+\lambda^2)(p^2+\lambda^2)}{h^2[(p^2+\lambda^2)(q^2+\lambda^2)]^{3/2}} \\
& \times\left[(h^2-q^2)\Pi\left(\frac{p^2}{h^2},\frac{p}{q}\right) - h^2K\left(\frac{p}{q}\right)\right],
\end{aligned}
$$

$$
\begin{aligned}
A_{0\mathrm{h}} = {} & -\frac{\lambda}{h^3q\sqrt{(p^2+\lambda^2)(q^2+\lambda^2)}} \\
& \times\left[h^2q^2E\left(\frac{p}{q}\right) - h^2(h^2+q^2)K\left(\frac{p}{q}\right)\right. \\
& \left. + (h^4-p^2q^2)\Pi\left(\frac{p^2}{h^2},\frac{p}{q}\right)\right].
\end{aligned}
$$

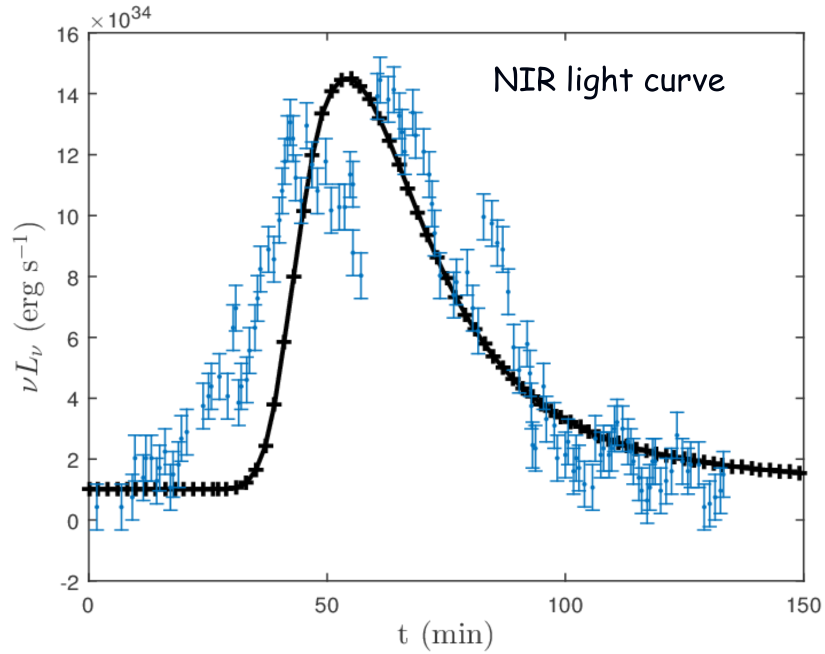
Catastrophic dynamical evolution of the current sheet and flux rope

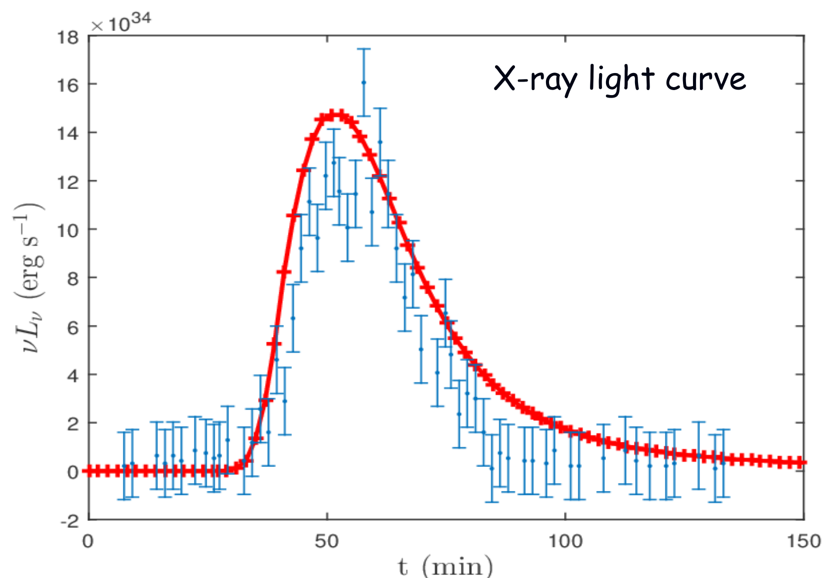
Li et al. 2016, in preparation

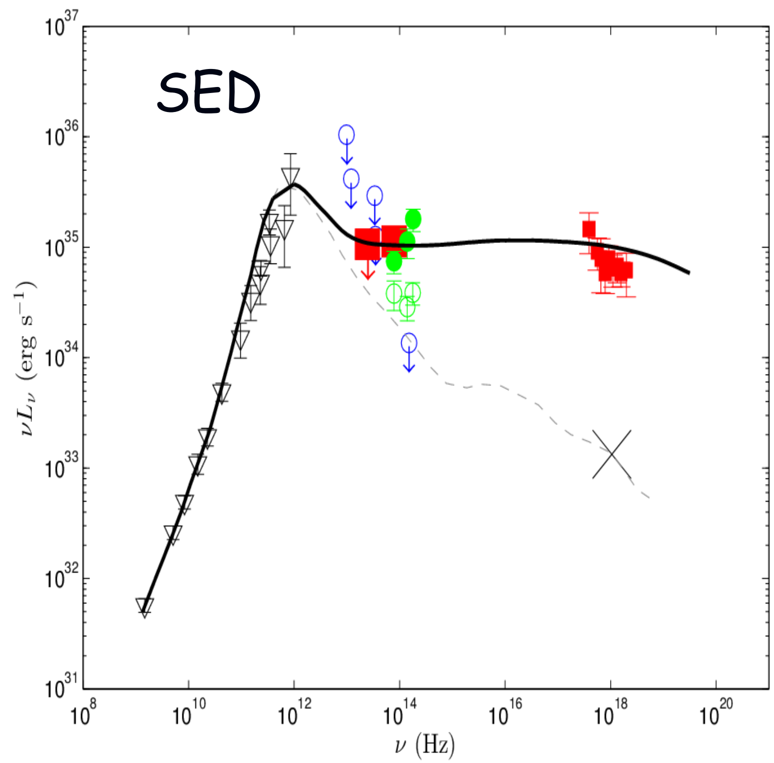




NIR & X-ray Light curves and SED







Main features:

1. Simultaneous flaring
2. Quasi-symmetric profile
3. Amplitudes both in NIR and X-ray

Summary

- Statistics of flares:

  Power law indexes, $\alpha_E \sim -1.6$ and $\alpha_{ET} < 0.55$, are consistent with S = 3 SOC theory
- Magnetic reconnection at the surface of accretion flow is likely the origin of X-ray flares
- We propose an MHD model for flares by analogy with solar flares/CME, motivated by the statistical results
- Our model reasonably explains the observed flare light curves and SED

Thank you!