黑洞附近发生的类太阳耀斑过程

袁 峰

复旦大学天文与天体物理中心

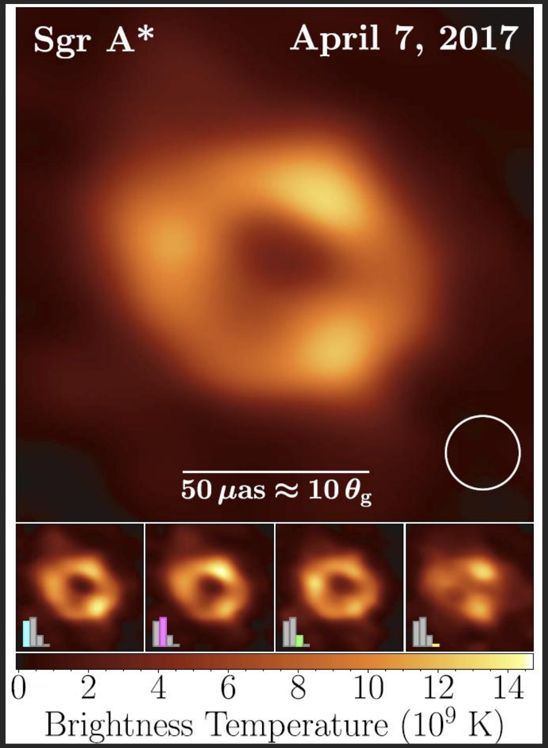
天关卫星时代的恒星X射线耀发研究 2025.5.26-28

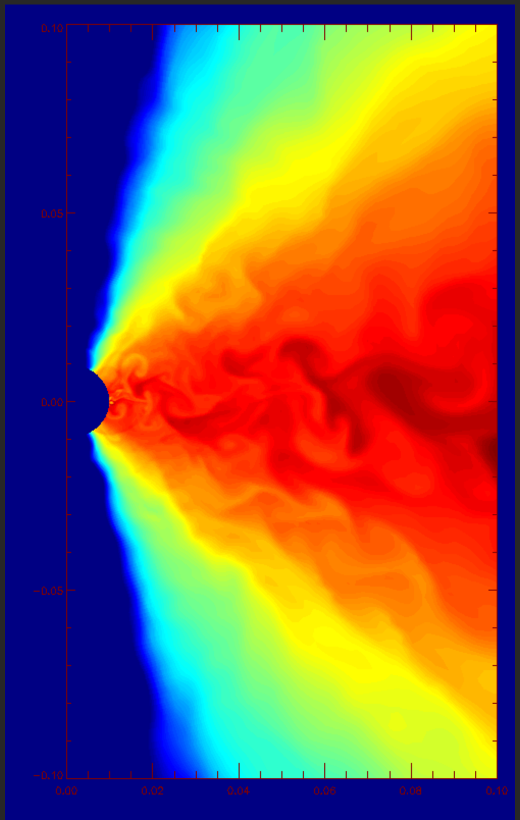
OUTLINE

- Observations of flares from BHs
- MHD model for flares & episodic jet: basic scenario
- Interpreting GRAVITY observations of Sgr A*:
  - Light curve & spectrum
  - Ejection speed
  - Blob trajectory & super-Kepler motion
- Another application: QPE

Sgr A*

- The supermassive BH in the Galactic center
- Quiescent state
  - $L_{\rm bol} \sim 10^{36}\ {\rm erg\ s^{-1}} \sim 10^{-9} L_{\rm Edd}$ for $M_{\rm BH} = 4\times10^{6} M_{\odot}$ ($\eta \sim 10^{-6}$);
  - RIAF model (Yuan et al. 2003)

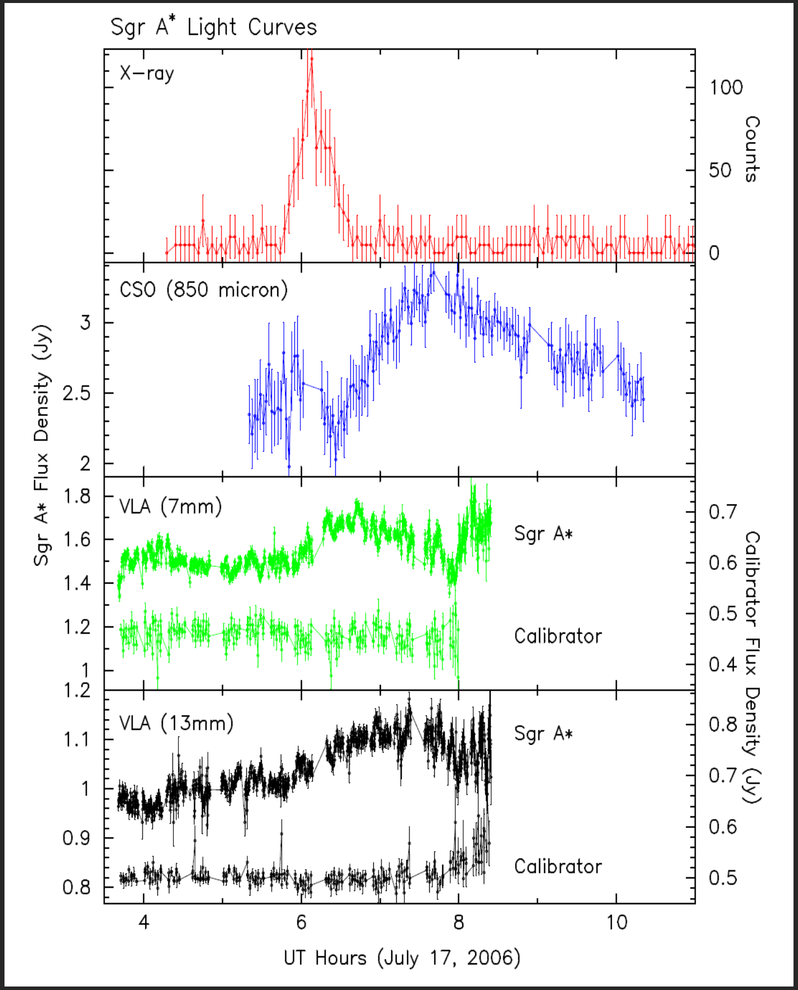




Flares from Sgr A*

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

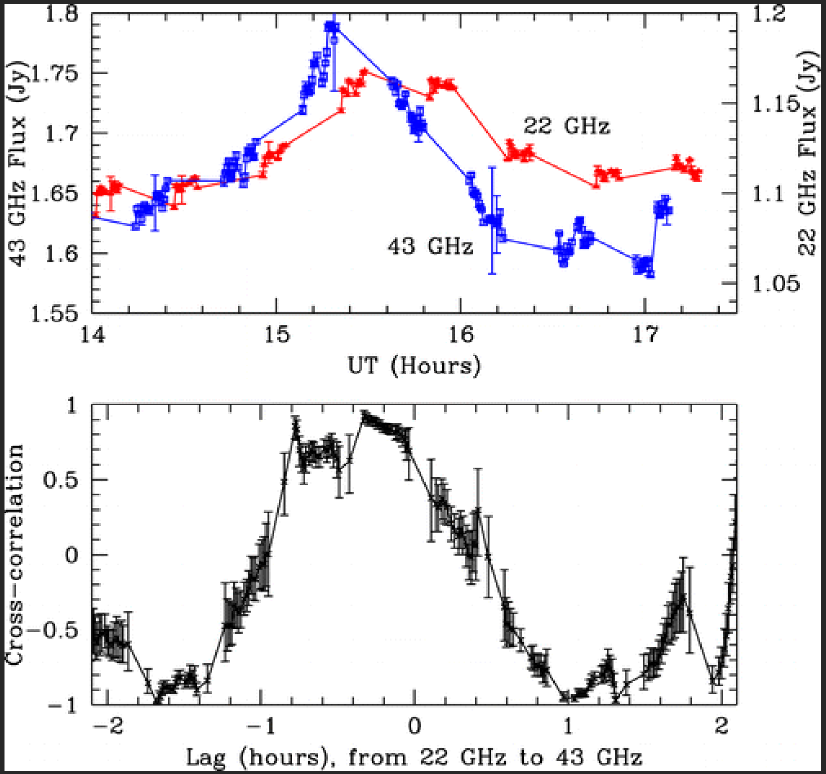
- NIR ~ 60 mins, several times/day
- X-ray ~ 30 mins; 400 x higher
- X-ray & NIR flares: simultaneous
- Followed by submm & radio flares
- Occurrence rate:
  - IR: ~ 4/day
  - X-ray: ~ 1/day



Yusef-Zadeh et al. 2008

Associated with plasma ejections

Yusef-Zadeh et al 2006; Marrone et al. 2008; Rauch et al. 2016



* Two light curves
* Such light curves are usually explained by the emission from a discrete blob (why?)
* VLBA observations at 7 mm detect a blob 4.5 hour after the flare, with velocity ~ 0.4 c

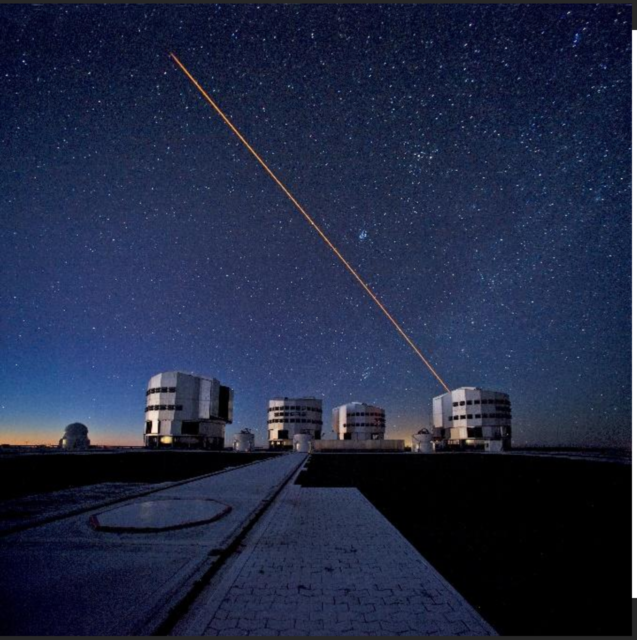
Yusef-Zadeh et al. 2006, ApJ

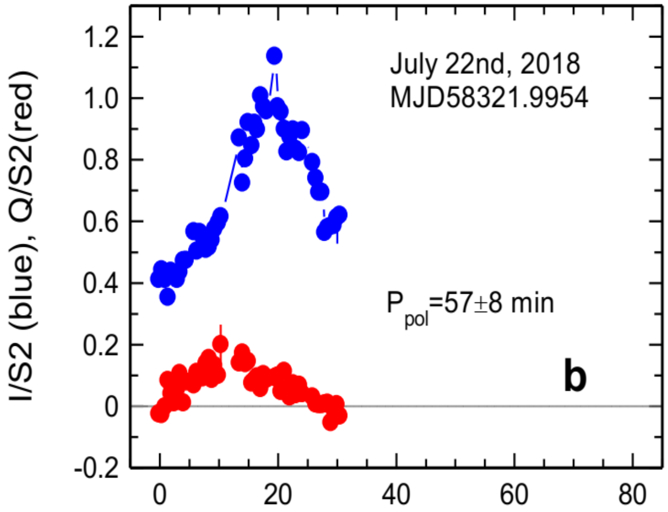
GRAVITY observations

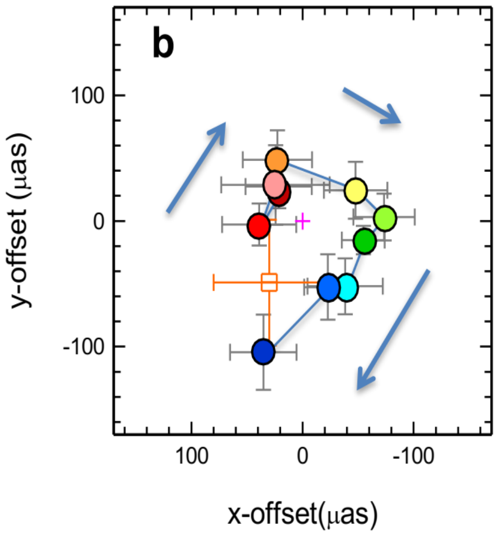
GRAVITY Collab. 2018, A&A

- NIR flares are associated with orbiting hot spots
- Orbital period ~45 mins for spots
- Located at $6 \sim 10\ R_g$ (increase with time)
- polarization

} Super-Keplerian!



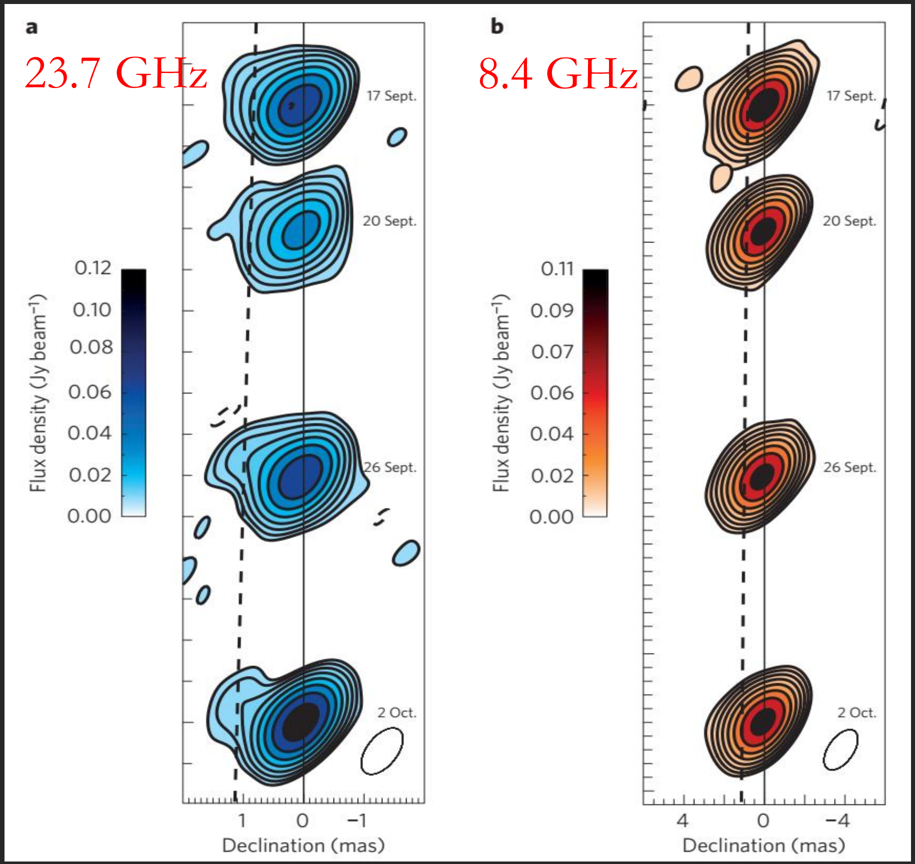


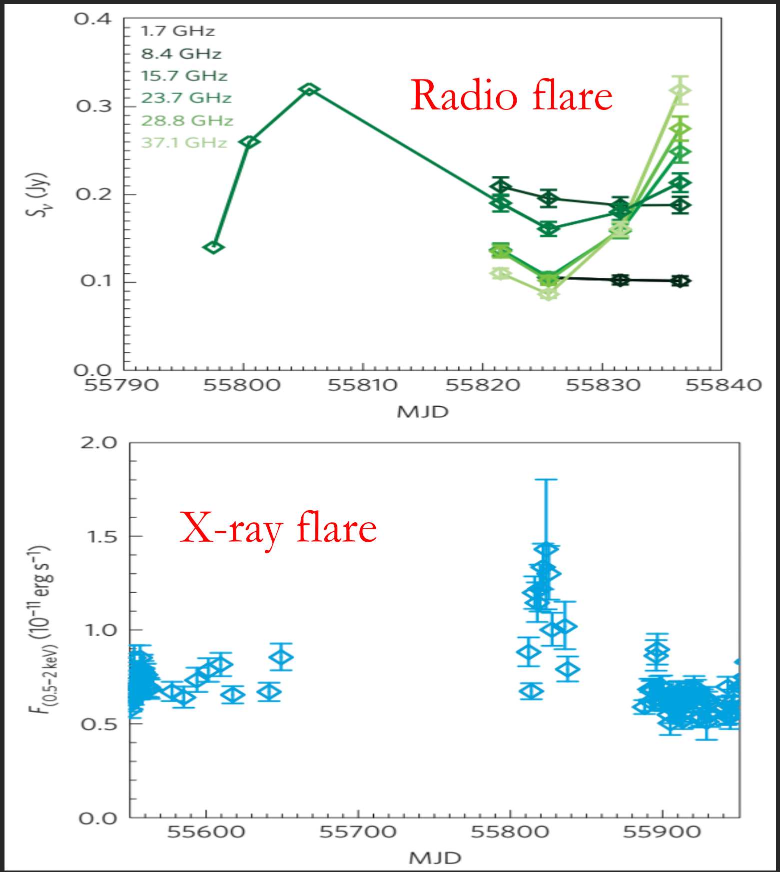


Flares and ejections in M81*

(King et al. 2016, Nature Physics)

- Radio flare delays with X-ray flares ~12 days (cooling timescales).
- A moving blobs associated with radio flare, v ~ 0.5 c @ ~ 10^4 r_g





Incomplete list of observational works:

- Hjellming & Rupen 1995, Nature
- Baganoff et al. 2001, Nature
- Wilms et al. 2007, ApJ: Cygnus x-1
- Marscher et al. 2008, Nature
- Hada et al. 2014, ApJ: M87
- King et al. 2016, Nature Physics
- Reynolds et al. 2017, ApJ: Mrk 231
- Park et al. 2019, ApJ: PKS 1510-089
- …..

What is the physical origin?

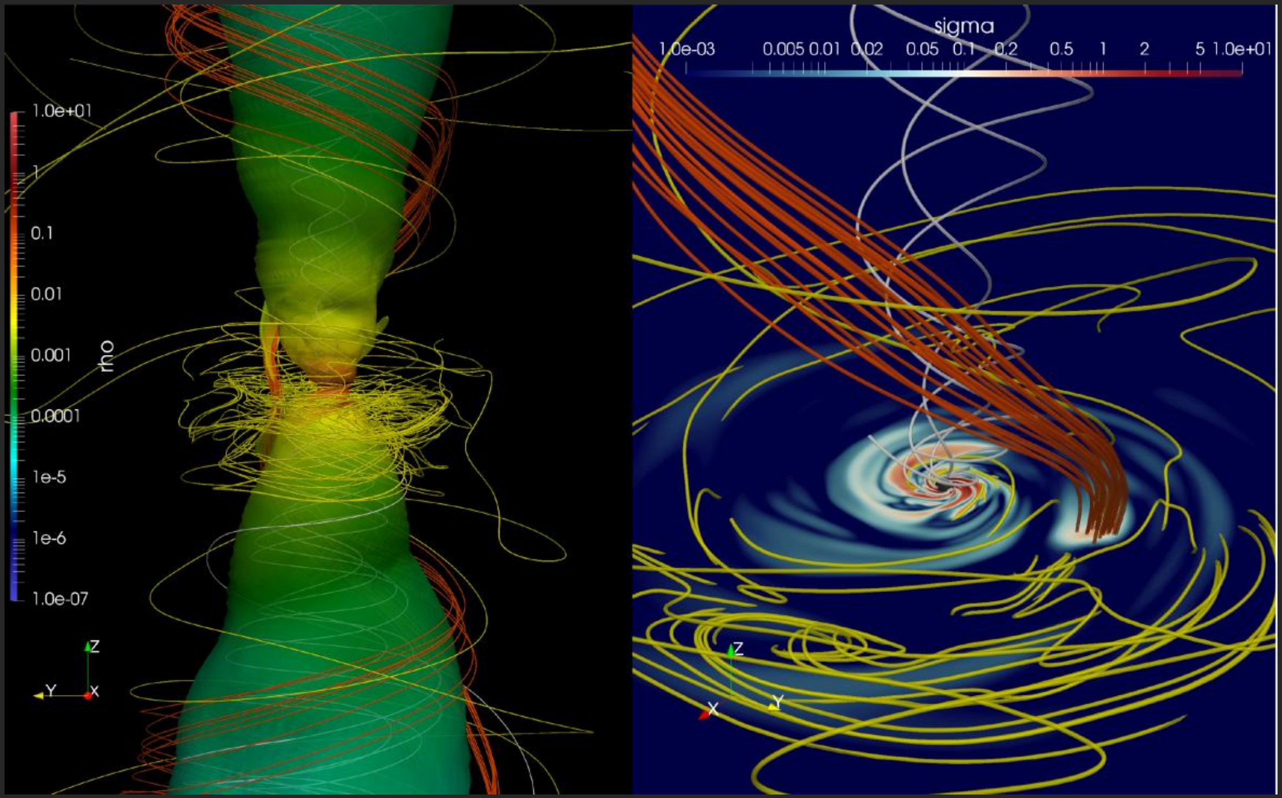
Proposed models for Sgr A* flares

- **Previous 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 (e.g., 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)
- **Current model:**

  magnetic reconnection in accretion flow

  (Ball et al. 2016,2021; Nathanail et al. 2020, 2022; Porth et al. 2020; Petersen & Gammie 2020; Dexter et al. 2020; Ripperda et al. 2020,2022; Chatterjee et al. 2021; Scepi et al. 2022; White & Quataert 2022)

Current flare model: an example



- 3D GRMHD simulations.
- Magnetized blobs formed within accretion flow, associated with flares.

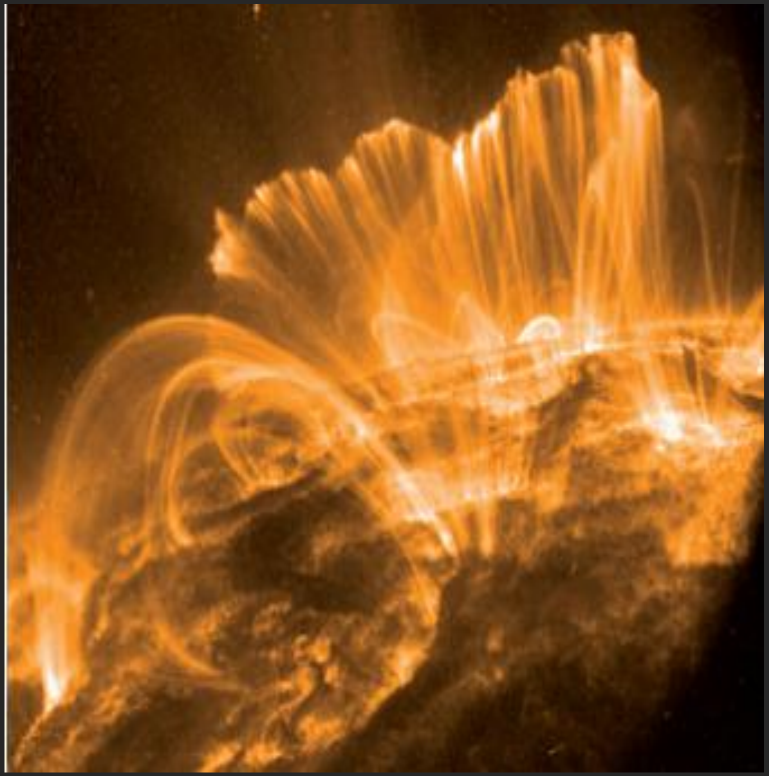
Porth et al. 2021

Two Problems:

- Trajectories of blobs should be sub-Keplerian (because they stay within the accretion flow.)
- Difficult to explain the association of flares with ejections

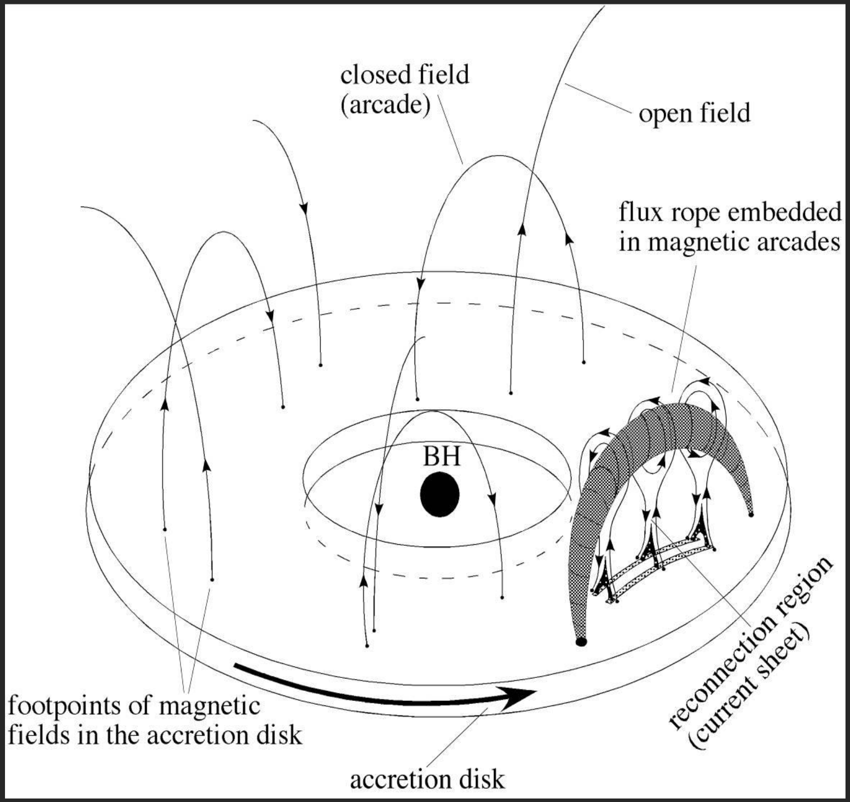
Solar flares and coronal mass ejections (CMEs)

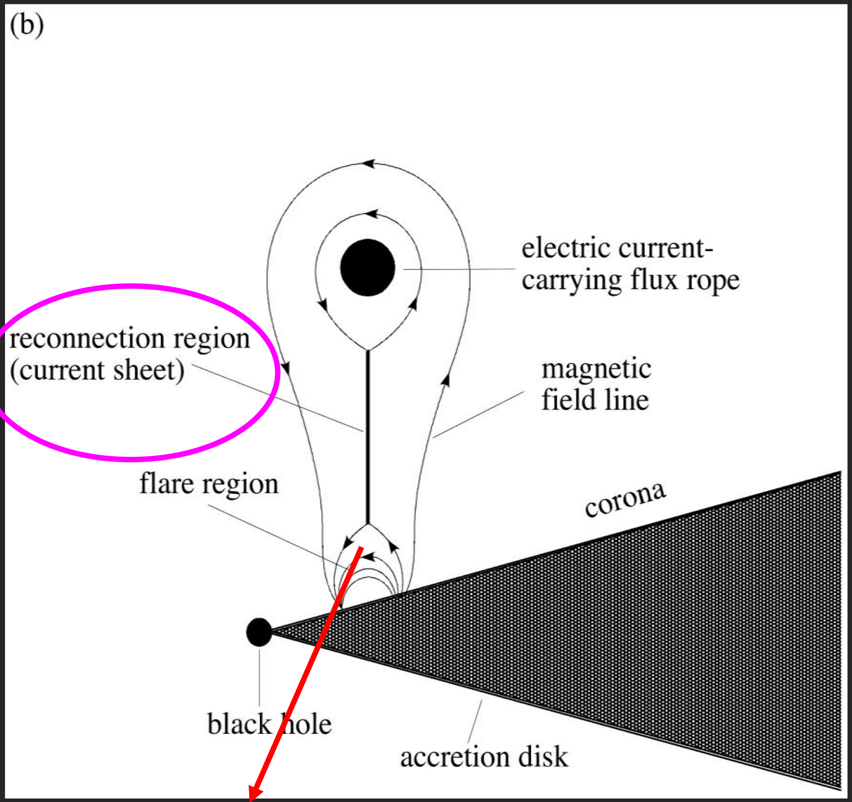
- Solar flares are very common.
- Flares in our Sun are accompanied with coronal mass ejections (CMEs).
- Flares are powered by magnetic reconnection in the solar atmosphere.



An MHD Model for flare & ejection of blobs

Yuan, Lin, Wu & Ho 2009

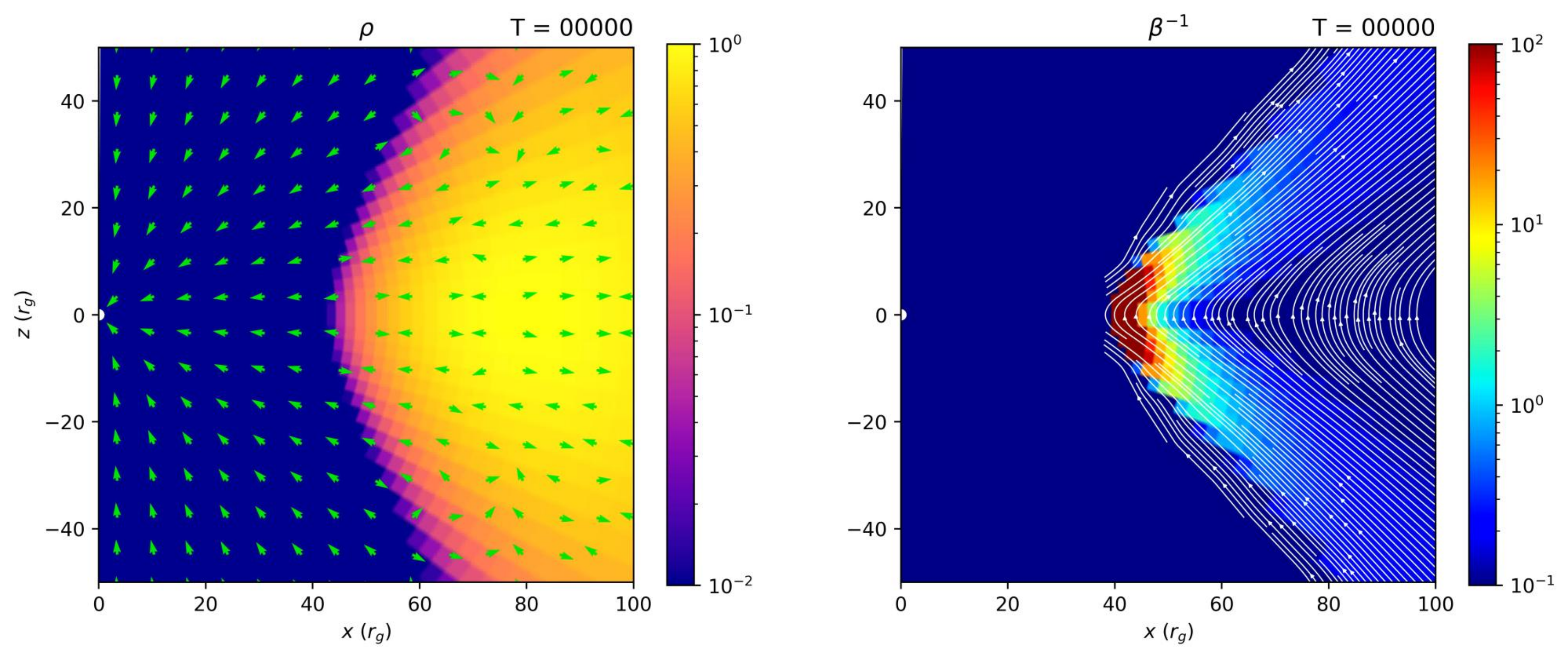




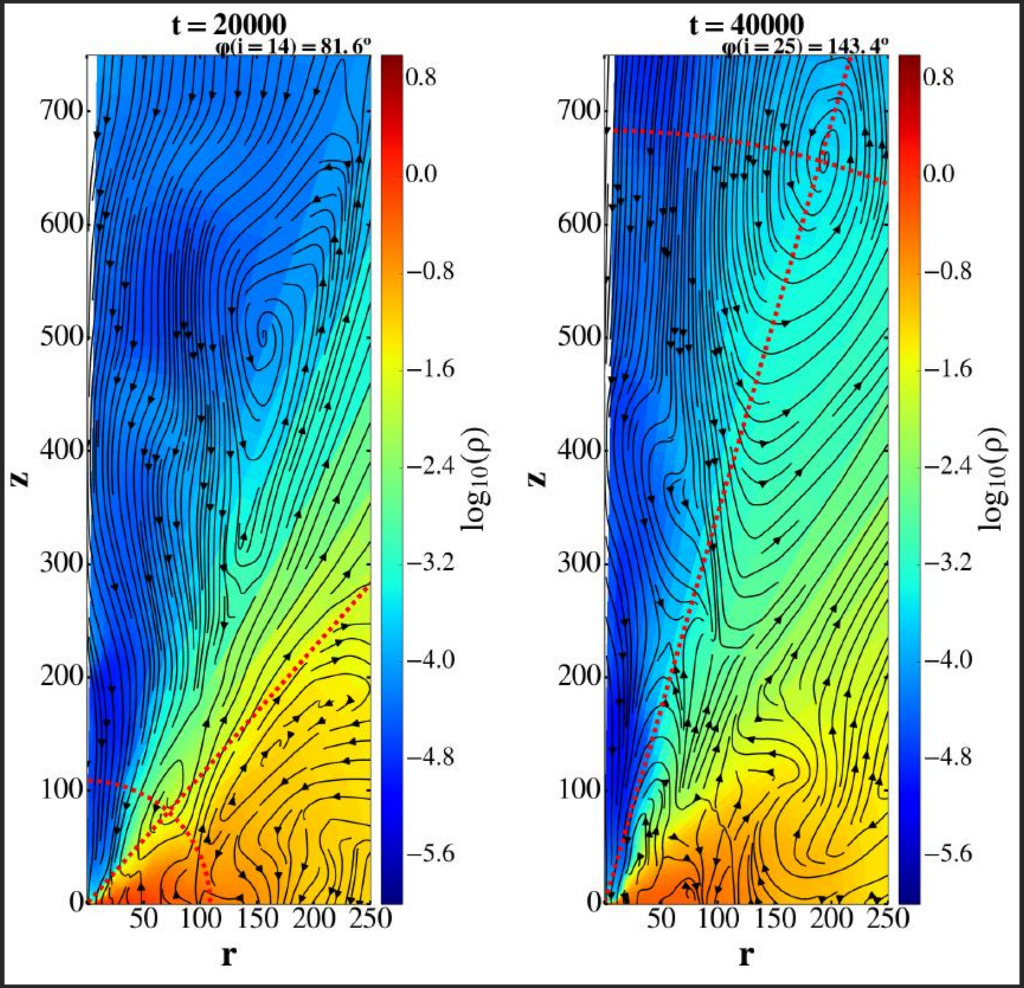
synchrotron of electrons accelerated by reconnection: IR & X-ray flares

3D GRMHD simulations to test Yuan et al. 2009

(Čemeljić, Yang, Yuan, Shang 2022)



Formation of flux rope

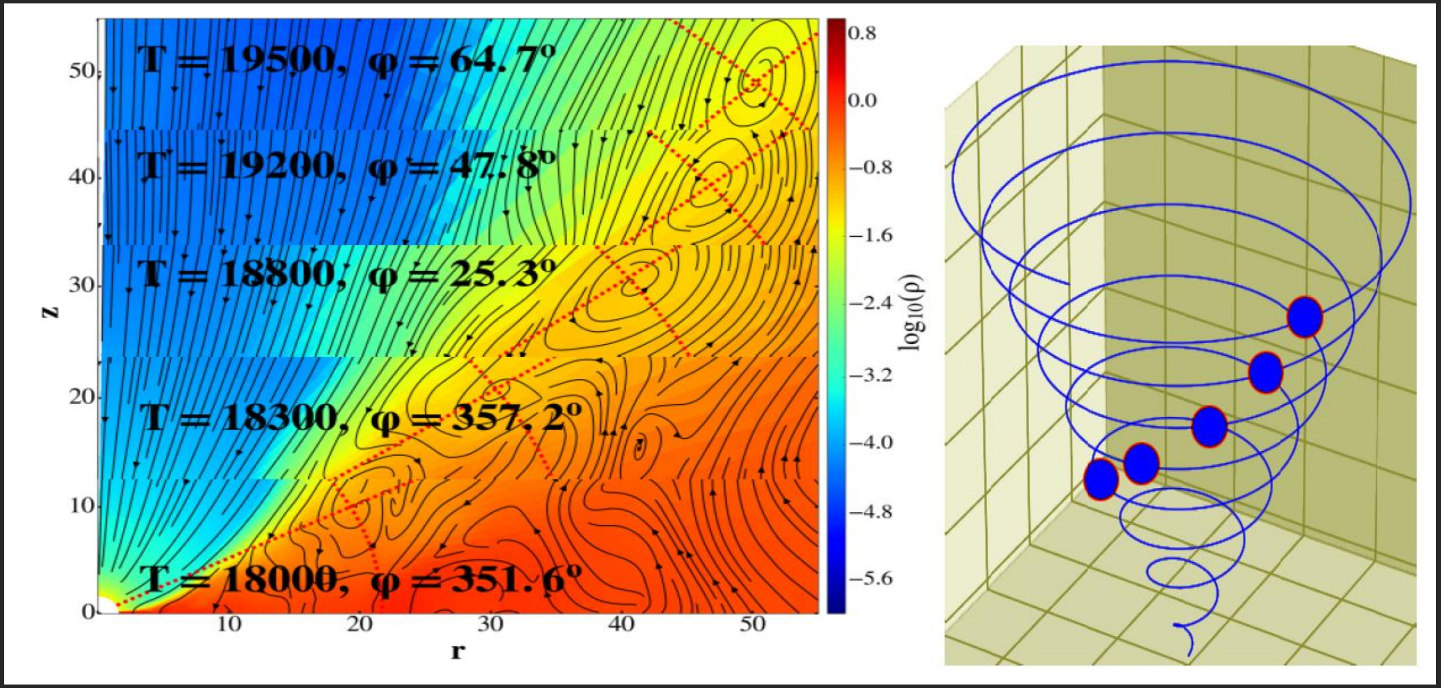


Čemeljić, Yang, Yuan, Shang 2022

- Formed due to **magnetic reconnection**, driven by turbulence & differential rotation of accretion flow
- Magnetic reconnection accelerates electrons, and produces flares

Flux rope ejection

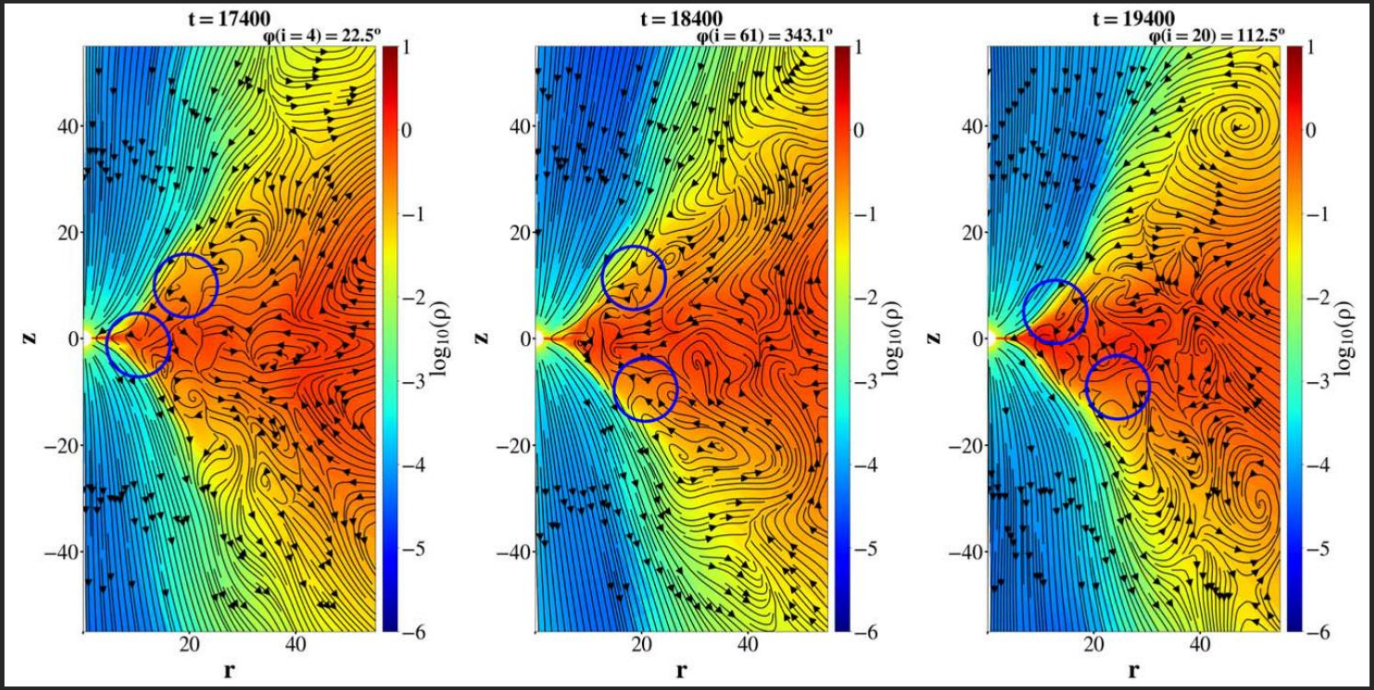
Čemeljić, Yang, Yuan, Shang 2022



- Fate of ejected blobs:
  - those beyond 10~15 Rg can be ejected out, with v ~ 0.08-0.3c
  - those inside this radius stay accreted by the BH
- Ejection is due to magnetic force (magnetic pressure gradient)

A new finding: periodicity

Čemeljić, Yang, Yuan, Shang 2022

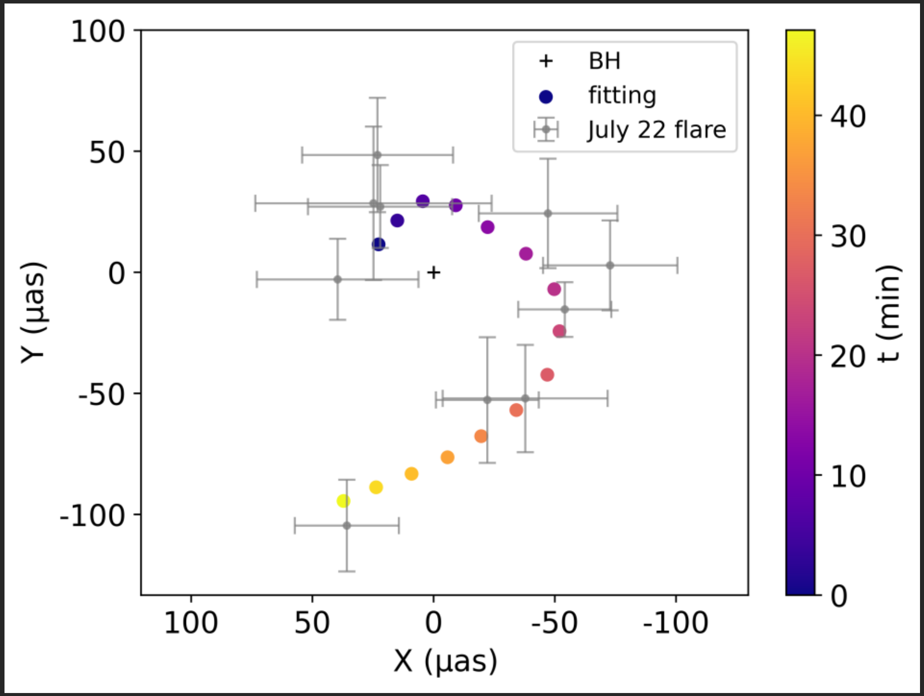


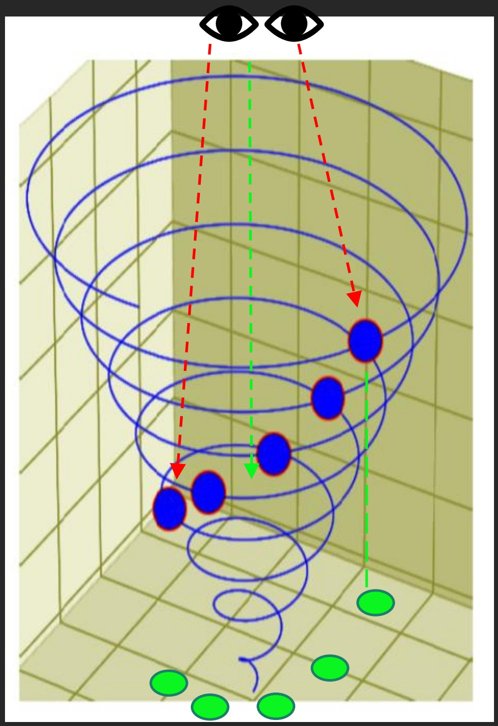
- Formation of flux rope has periodicity, with period ~ 1000 r_g/c
  - Physical mechanism? differential rotation? Chen & Yuan 2025, in preparation

Results: hot spot trajectory and super-Keplerian motion

Lin & Yuan 2024, MNRAS

- We directly find a flux rope from simulation data, with trajectory consistent with observation
- Super-Keplerian motion:
  - Rotation of the flux rope is sub-Keplerian
  - But increases to ~0.96 Ω_K at projected plane
  - Light aberration effect → super-Keplerian





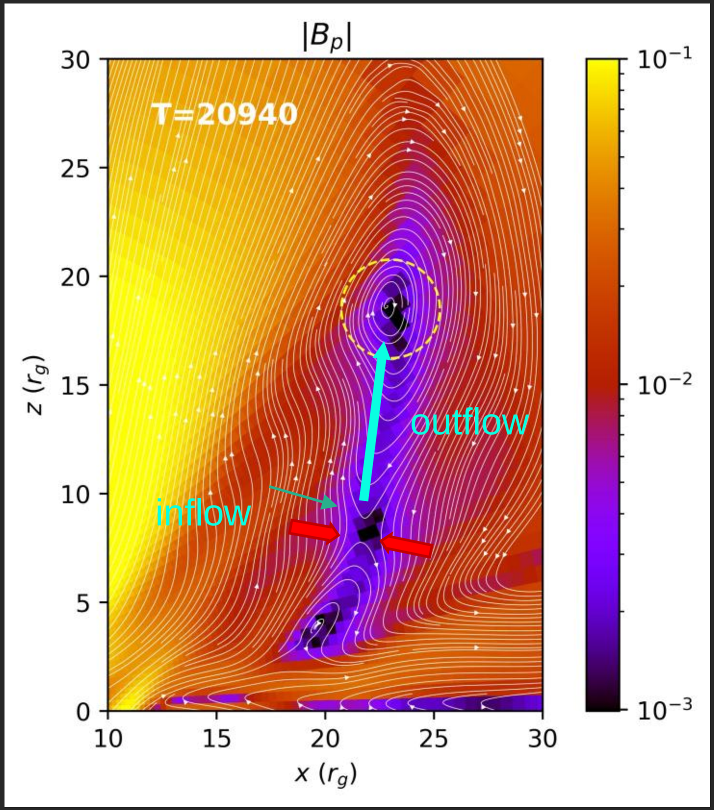
Radiation calculation

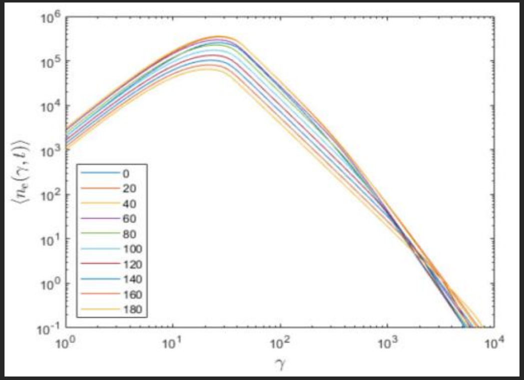
Lin & Yuan 2024, MNRAS

- Injected inflow power of Poynting flux: $\iint \frac{1}{4\pi} B^2 v \mathrm{dA}$
- 10% are dissipated to accelerate electrons to power law distribution
- Continuous injection: $Q_{\mathrm{inj}} = c\gamma^{-p}, \gamma_{\min} \leq \gamma \leq \gamma_{\max}$
- Solve for the time-dependent energy distribution of nonthermal electrons (radiative & adiabatic cooling):

$$\frac{\partial N_{\mathrm{e}}(\gamma, t)}{\partial t} = Q_{\mathrm{inj}}(\gamma, t) - \frac{\partial\left[\dot{\gamma} N_{\mathrm{e}}(\gamma, t)\right]}{\partial \gamma}$$

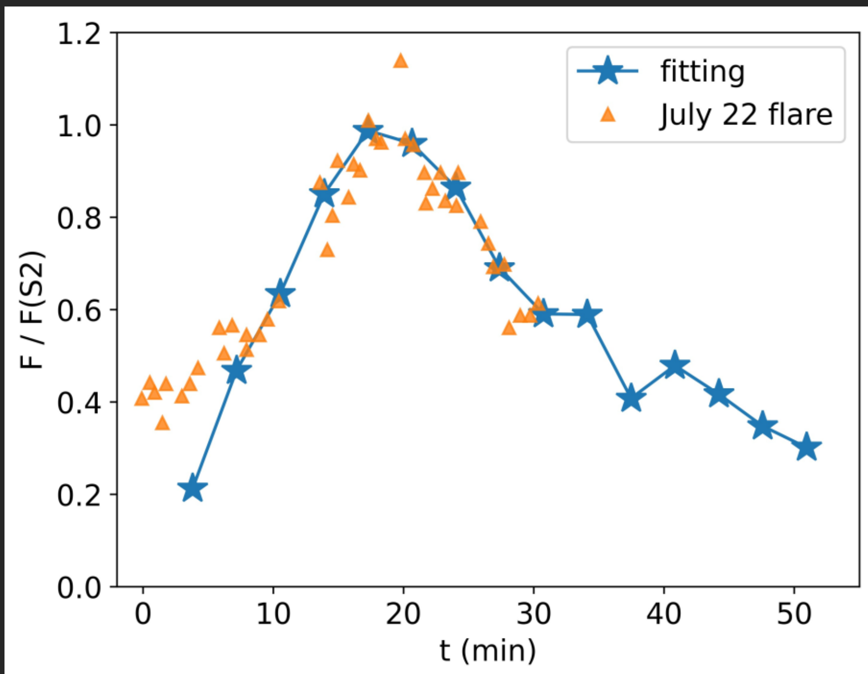
- GR ray-tracing radiative transfer

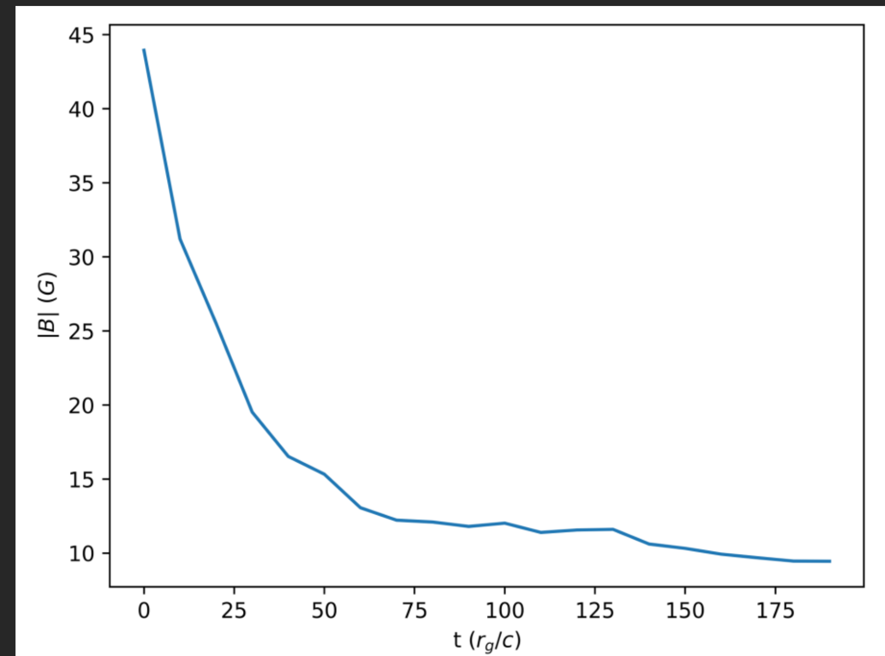




Light curve

Lin & Yuan 2024, MNRAS

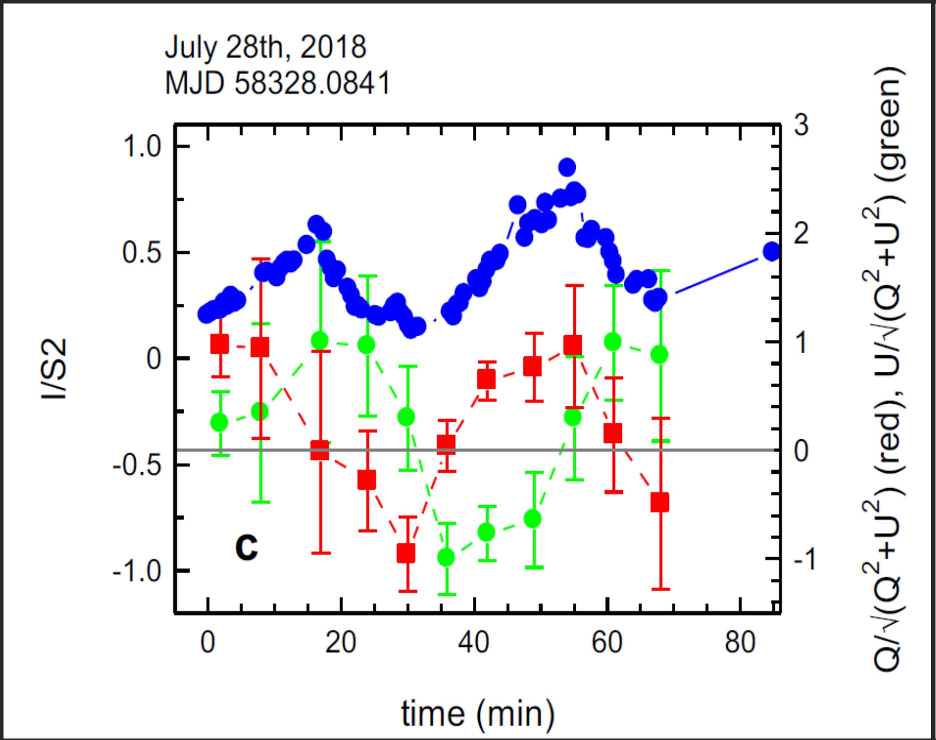


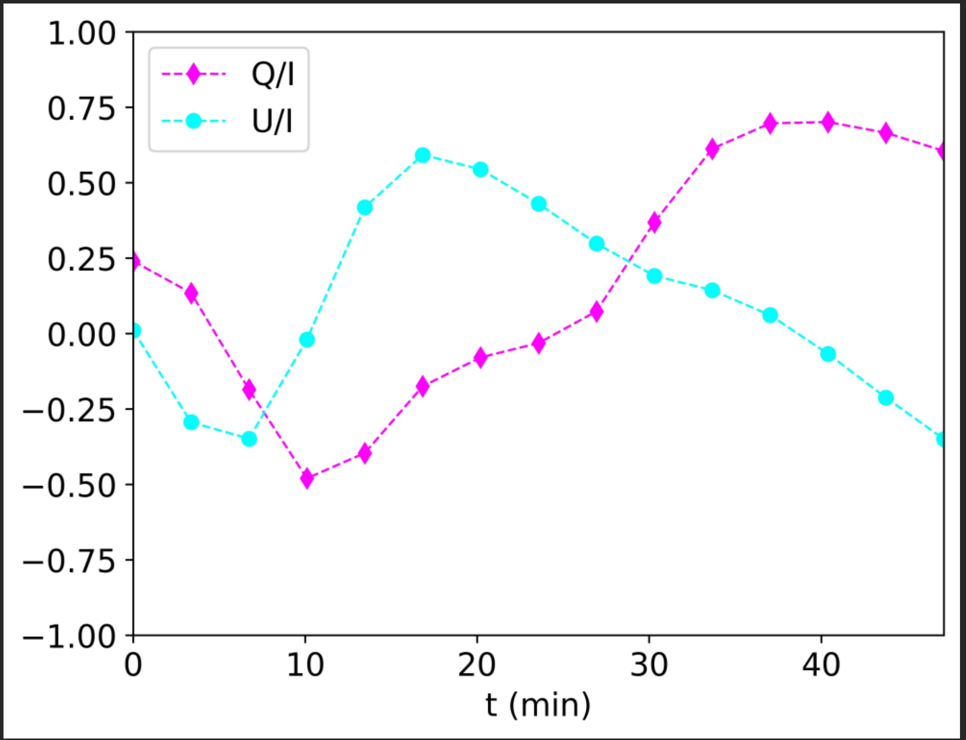


- The rise of the light curve is mainly caused by the injection of the non-thermal electrons
- The decay of the light curve is due to:
  - Decrease of field strength
  - Decrease of the injection power
  - Radiative cooling

Polarization

Lin & Yuan 2024, MNRAS





*The period of rotation of polarization consistent with GRAVITY.
*Polarization degree higher than observed value.

Thank you!