# Physical processes around a black hole driven by magnetic reconnection


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**Transient Phenomena and Physical Processes Around Supermassive Black Holes; TD Lee Institute, 10.15-18, 2024**

# Particle acceleration and radiation of jet

Yang, Yuan *et al. Science Advances* 10, eadn3544 (2024)

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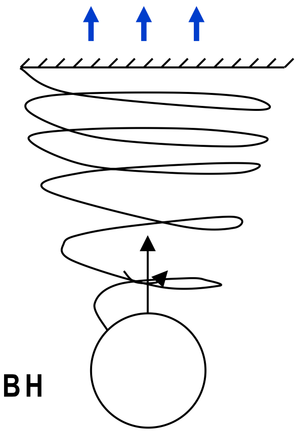
# Models of jet formation (I) : Blandford-Znajek model

- Blandford-Znajek model (Blandford & Znajek 1977)
  - Spinning black hole
  - Large-scale poloidal magnetic field anchored to the horizon
  - Extracting the spin energy of the BH with poloidal B field

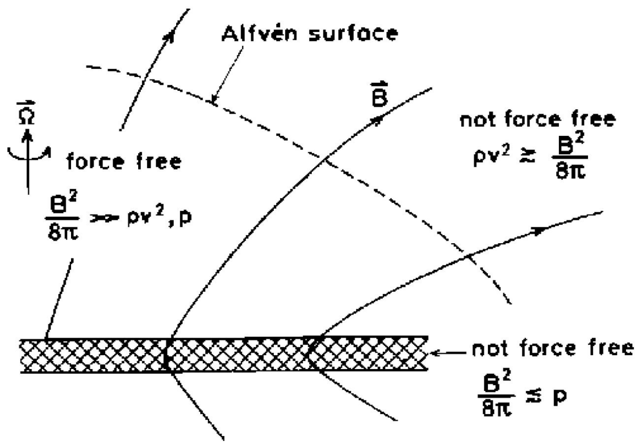
$$P = \frac{B_\varphi^2}{8\pi}$$

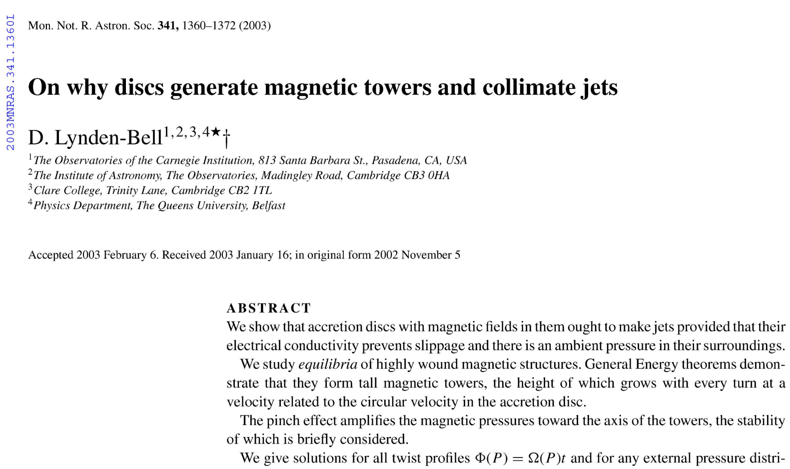



Roger Blandford

# Models of jet formation (II): Blandford-Payne and Magnetic tower models

- Blandford-Payne model (Blandford & Payne 1982)
  - Large-scale ordered poloidal field
  - Suitable inclination angle
  - Extracting the spin energy of the accretion flow with poloidal B field via magnetocentrifugal force
- Magnetic tower model (Lynden-Bell 2003)
  - Similar to BZ model, but extracting the spin energy of the accretion flow
  - Confirmed by numerical simulations





Mon. Not. R. Astron. Soc. **341,** 1360–1372 (2003)

**On why discs generate magnetic towers and collimate jets**

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**ABSTRACT**
We show that accretion discs with magnetic fields in them ought to make jets provided that their electrical conductivity prevents slippage and there is an ambient pressure in their surroundings.

We study *equilibria* of highly wound magnetic structures. General Energy theorems demonstrate that they form tall magnetic towers, the height of which grows with every turn at a velocity related to the circular velocity in the accretion disc.

The pinch effect amplifies the magnetic pressures toward the axis of the towers, the stability of which is briefly considered.

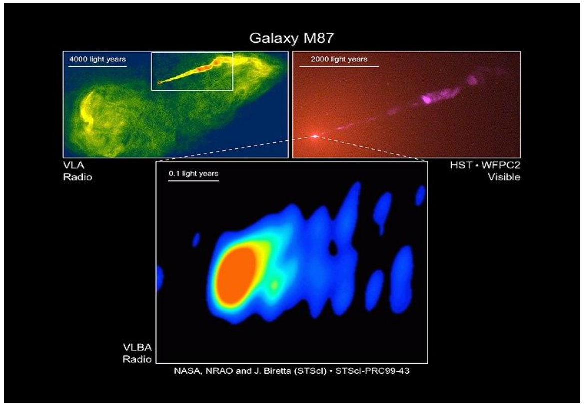
We give solutions for all twist profiles $\Phi(P) = \Omega(P)t$ and for any external pressure distri-

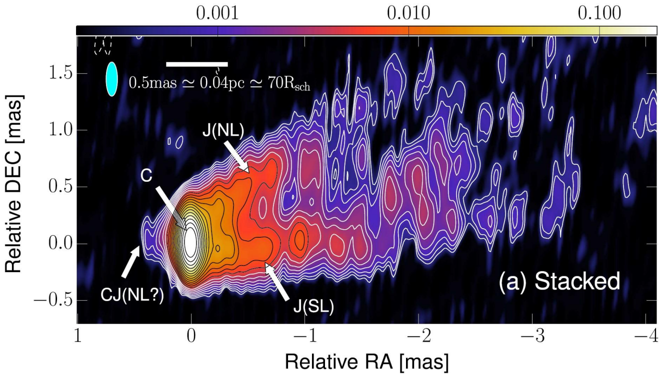
# Some open questions in jet physics

- BZ, BP:  Which dynamical model is correct?
- Whether BZ model can reproduce observations of jet?
  - Many observational constraints (not only jet power & SED)
  - Keys: electron acceleration and radiation mechanisms
- How  are electrons accelerated?
  - Internal shock (Bell 1978; Blandford & Eichler 1987)?
  - Magnetic reconnection? By what mechanism? Kink instability?

# Observational constraints of jets

- Spectral energy distribution:
  - many works
- Morphology: much more demanding
  - Elongated structure
  - Limb-brightening feature
  - Jet width as a function of distance
- Velocity field in the jet
- polarization



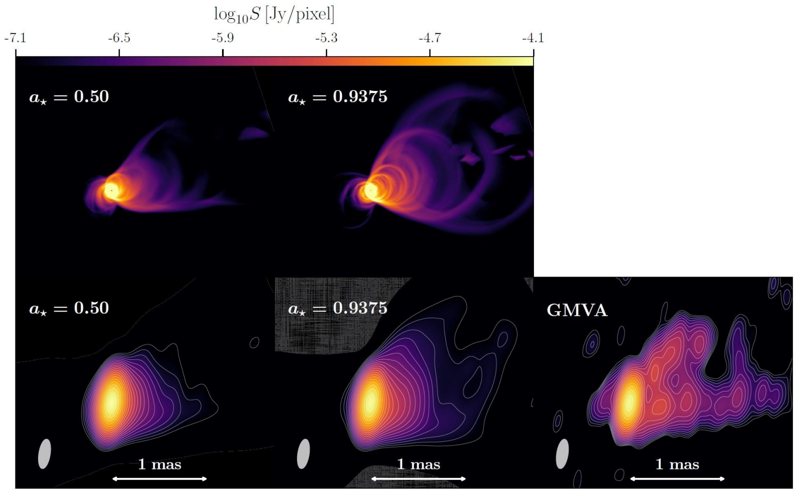

**Kim et al. 2018**

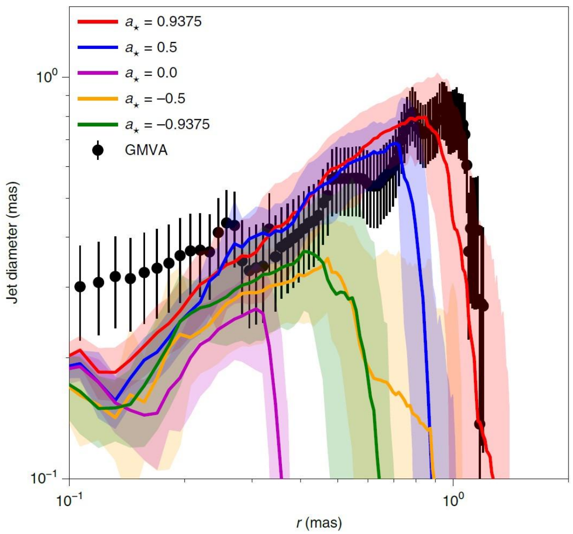
# Previous work：

# Cruz-Osorio et al. (2021 Nature Astronomy)

- GRMHD simulation to produce BZ jet
- Determination of number density of nonthermal electrons:
  - A constant fraction of thermal electrons in each place of the jet
- electron energy distribution
  - $\kappa$ distribution: $dn_{\rm e}/d\gamma_{\rm e} = N\gamma_{\rm e}\sqrt{\gamma_{\rm e}^2 - 1}\,[1 + (\gamma_{\rm e} - 1)/(\kappa w)]^{-(\kappa+1)}$
  - “Power-law Index” depends on $\beta$ & $\sigma$
- Radiative transfer calculation

# Results: Jet morphology and width



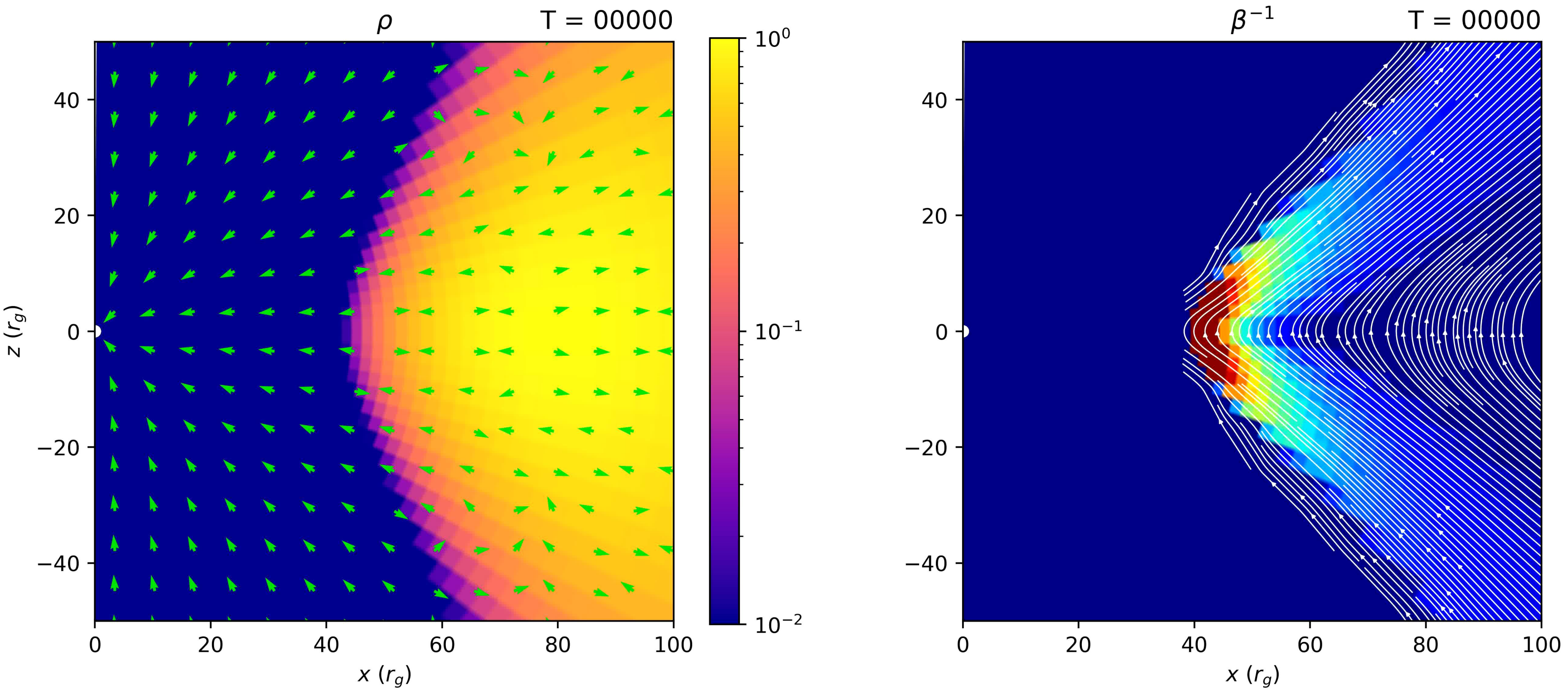

Successes:
1) Roughly reproduce jet morphology
2) SED
3) Roughly explain jet width

Problems:
1) Jet still too short
2) hard to explain limb-brightening
3) Underpredict jet width at small di

# 3D GRMHD simulation of jet

- Code: Athena++
- Four models:
  - MAD98, MAD05, MAD00, SANE98
- MAD98: 1408X512X256 (fiducial mode
- MAD05, MAD00, SANE98: 880X256X128
- SMR (static mesh refinement) to imp
  resolution in the jet region

| Level | $r / r_g$ | $\theta / \pi$ | $\varphi / \pi$ |
|---|---|---|---|
| 0 | [1.1, 1200] | [0, 1] | [0, 2] |
| 1 | [1.1, 200] | [0.1305, 0.8689] | [0, 2] |
| 2 | [1.1, 30] | [0, 1] | [0, 2] |
|  | [30, 1200] | [0.0722, 0.1667] | [0, 2] |
|  | [30, 1200] | [0.8333, 0.9278] | [0, 2] |
| 3 | [30, 1200] | [0.0555, 0.0722] | [0, 2] |
|  | [30, 1200] | [0.9278, 0.9444] | [0, 2] |
|  | [30, 1200] | [0.0055, 0.0555] | [0, 2] |
| 4 | [30, 1200] | [0.9444, 0.9944] | [0, 2] |



ρ
T = 00000
z (r_g)
x (r_g)
β^-1
T = 00000
x (r_g)

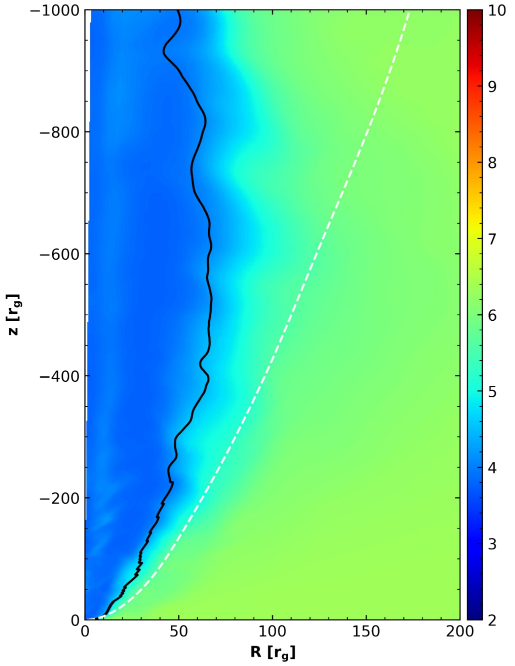
# *Determining thermal & nonthermal electrons in the jet*

- Thermal electrons $\frac{T_p}{T_e} = R_{low}\frac{1}{1+\beta^2} + R_{high}\frac{\beta^2}{1+\beta^2}$
- Particle acceleration by reconnection
- We assume electrons in jet are accelerated by reconnection and follows:

$$\frac{dn_{pl}}{d\gamma} = N_{pl}(p-1)\gamma^{-p}, \quad \gamma_{max} > \gamma > \gamma_{min}$$

- The value of p is determined by considering particle injection, acceleration, and escape, by making use of kinetic PIC simulations (Li et al. $p = \frac{1}{\sigma_x + 0.2(1+tanh(b_g))} + 0.04tanh(b_g)\sigma_x + 1.7b_g + 2.1$

$$B_g = b_g B_0; \sigma_x = \frac{B_0^2}{w}$$



# Number density of nonthermal electrons

- How to determine $N\_pl$ ? the most important parameter to determining jet morphology!
- Usually it is assumed to be a constant fraction of thermal electrons or magnetic field (Ozel, Psaltis & Narayan 2000; Broderick et al. 2016; Davelaar et al. 2018; Dexter et al. 2012)
- In our model, density of nonthermal electrons is determined by (based on PIC simulations; Peterson & Gammie 2020):

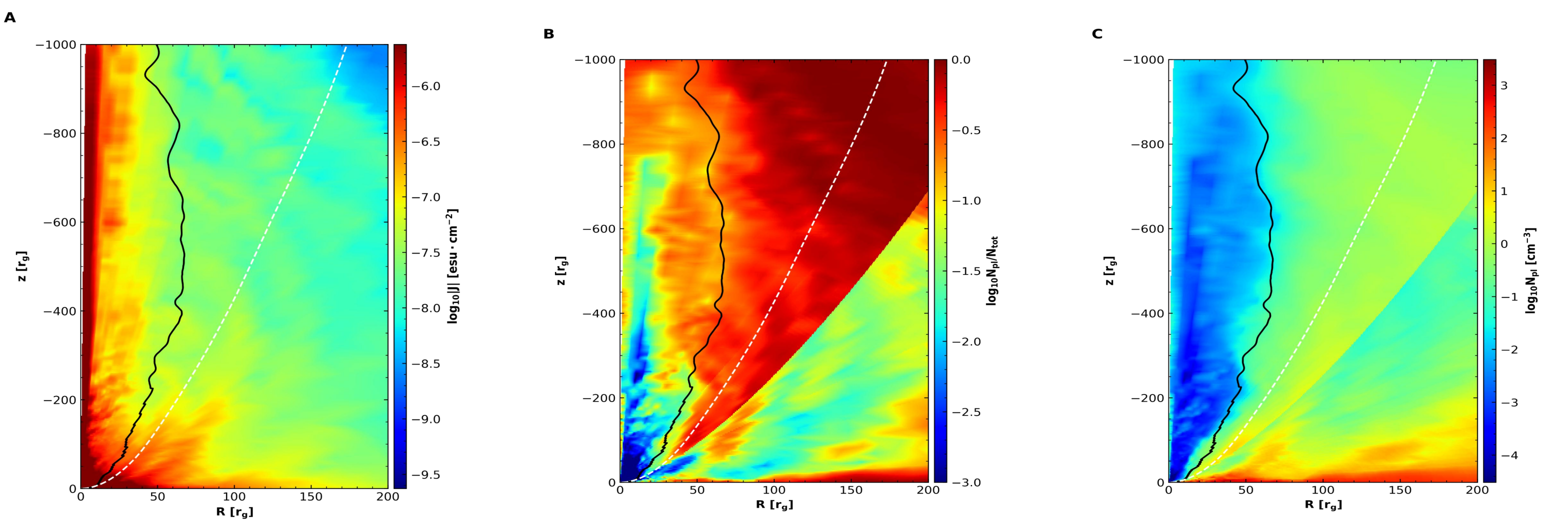
$$\propto \left(\frac{J}{J_0}\right)^2$$

$$J^i = \partial_j F^{ij} + \Gamma^i_{j\lambda} F^{ij}$$

- Calculation of $J$:
- Steady-state distribution obtained by:

$$\boxed{\eta \frac{v_A}{r_z}(N_{tot} - N_{pl})\frac{J^2}{J_0^2} = \frac{N_{pl}}{\tau_{cool}}}$$

# Distribution of number density of nonthermal electrons




- J is strongest in the jet axis & eq. plane
- $N_{pl}$ is largest in the equatorial plane
- Combining the distribution of B, the radio radiation within the jet is strongest.

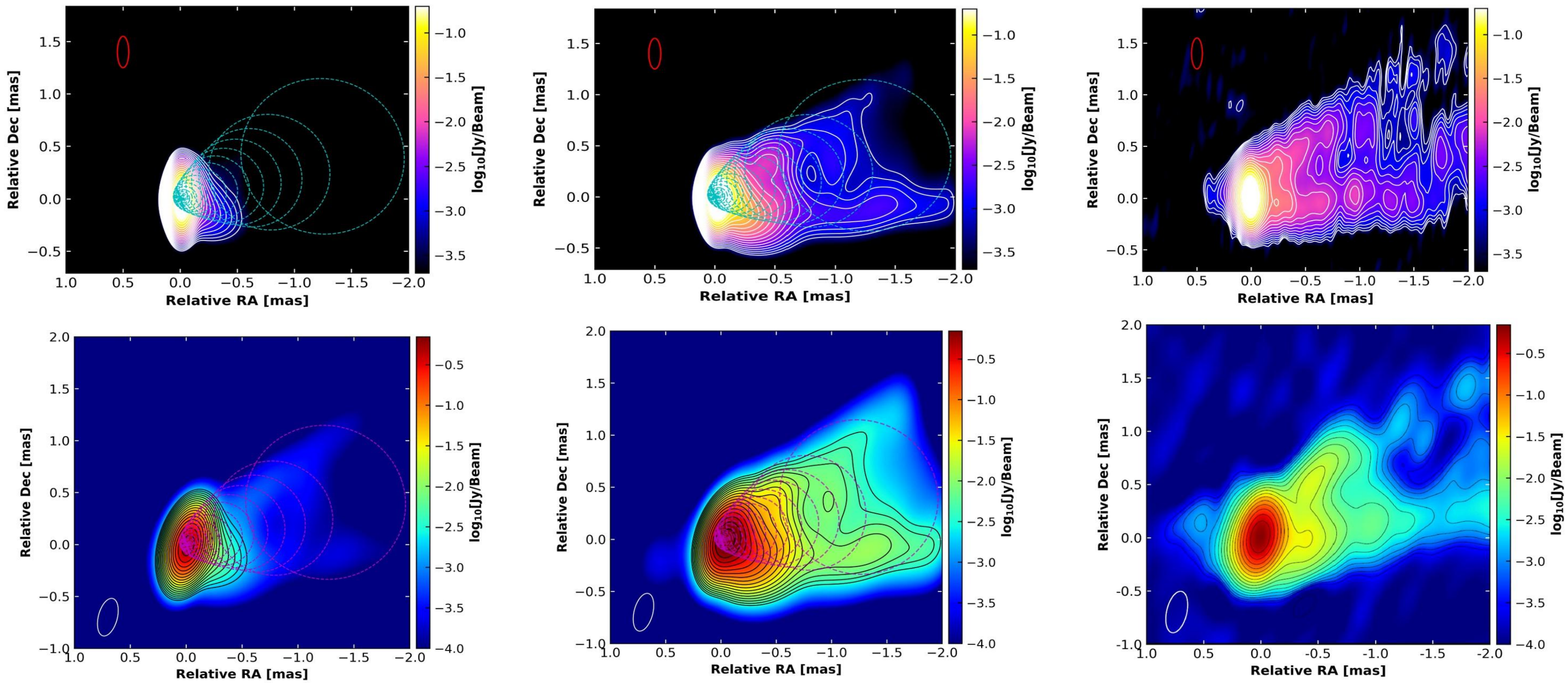
# Radiative transfer calculation and jet image

- The region of $\sigma > \sigma_{cut}$=5 is excluded (since the predicted thermodynamics is unreliable there)
- Normalize the density & B field of our MHD simulation by requiring predicted 230 GHz flux equal to EHT result
- Calculate the polarized radiative transfer using ray-tracing code IPOLE (Moscibrodzka & Gammie 2018)
- All plasma in the simulation domain is included (jet, wind, accretion flow)

# Predicted jet images

86 GHz

43 GHz



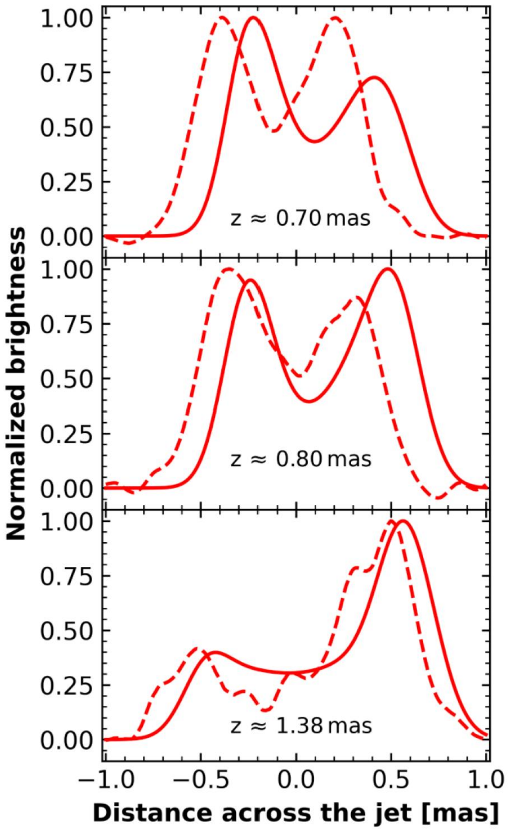

Thermal-only model

Current-density model

observations

The model can successfully reproduce the elongated structure of je

# Limb-brightening features

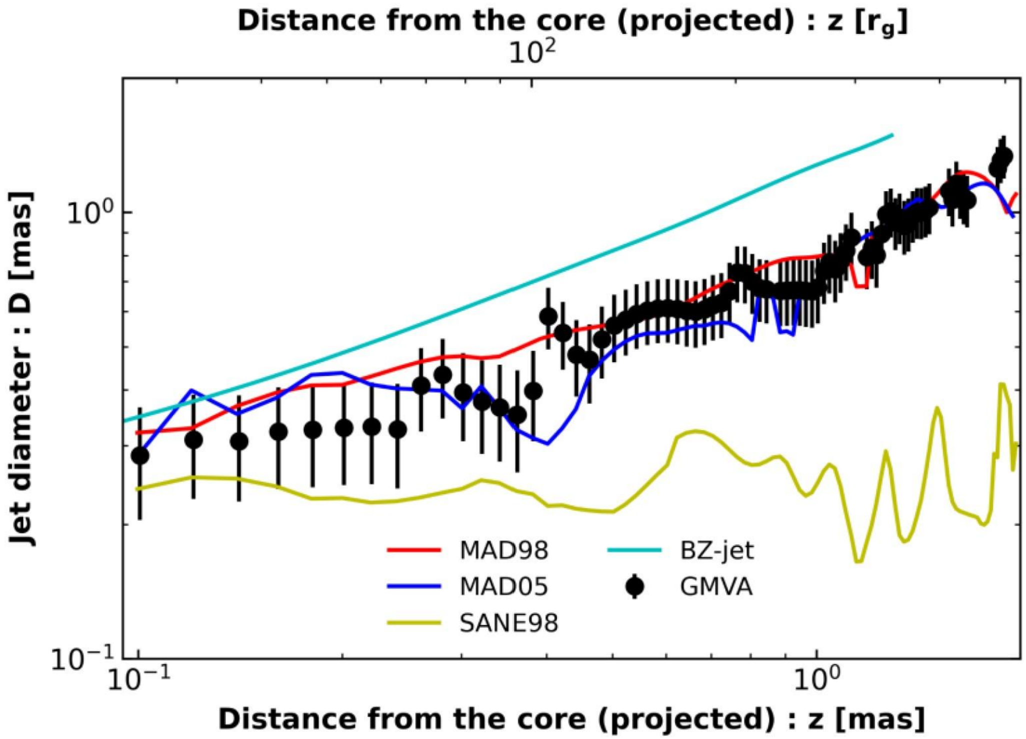



Dashed lines:
observed profiles

Solid lines:
predicted profiles of brightness by MAD98

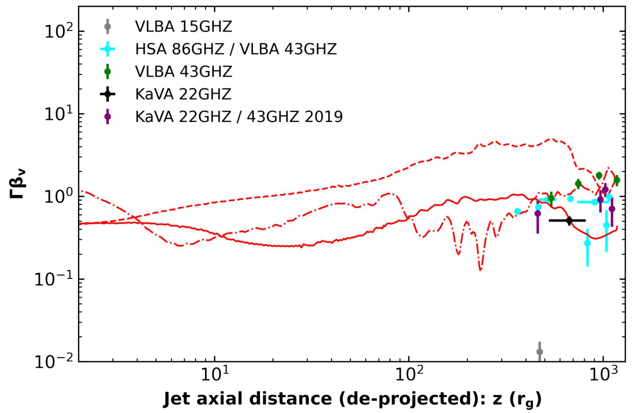
Conclusion:
Well consistent with observations and much better than previous works!

# Jet width

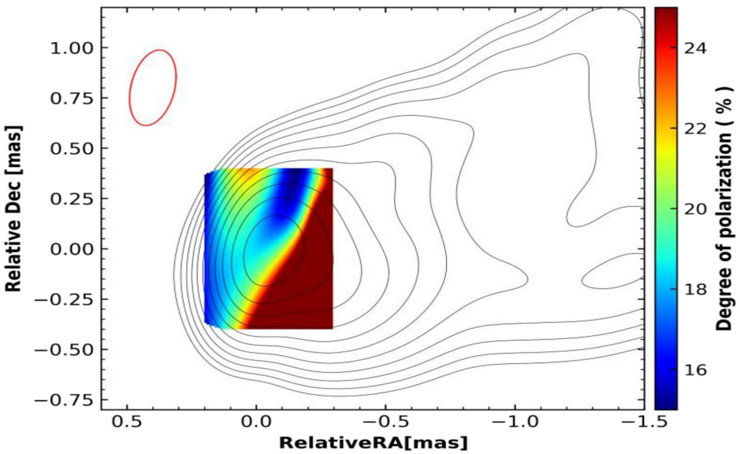



- BZ-jet of MAD98 consistent with observations
- BZ-jet of MAD05 worse; SANE98 ruled out
- BP jet over predicts the jet width thus ruled out

# Other observational constraints: Velocity, power, and polarization




Velocity field



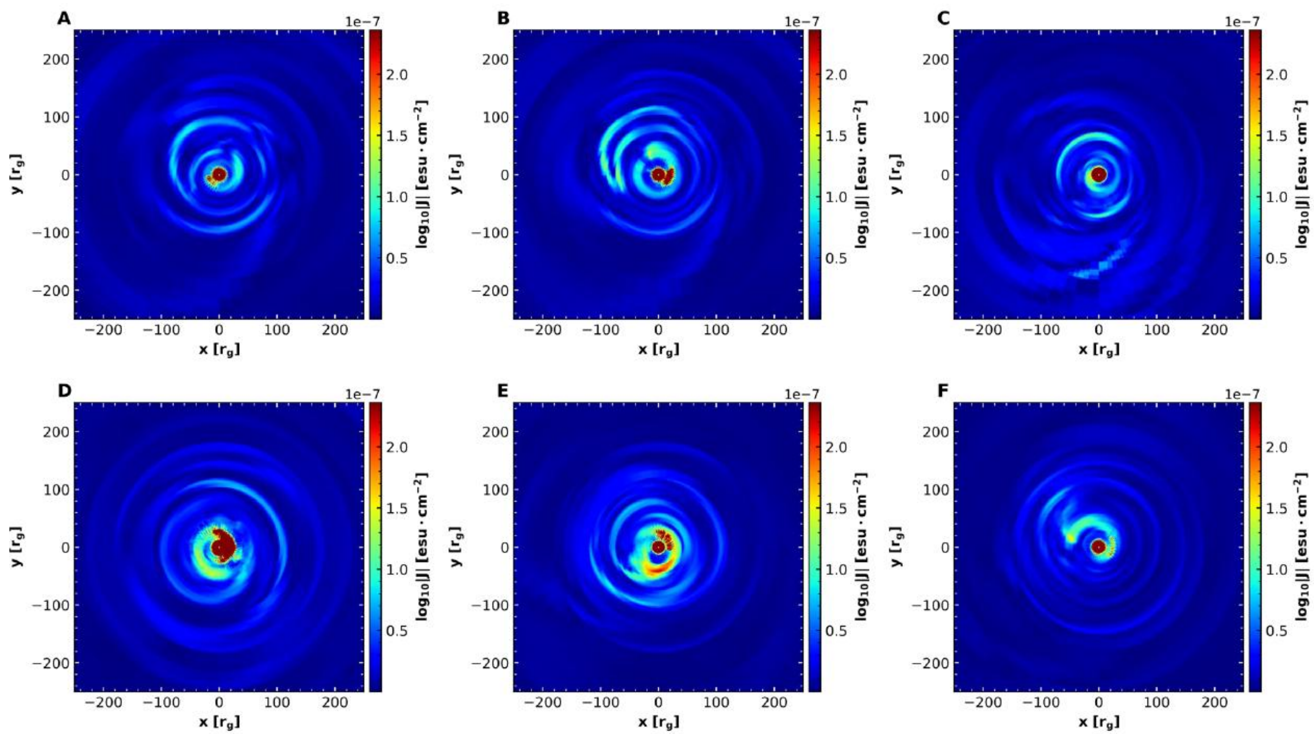

polarization

- $P_{jet}=6.32\times10^{43}\ erg\ s^{-1}$: consistent with observations
- Velocity field consistent with observations
- Polarization degree > observed degree: reasonable

# Driving mechanism of reconnection: Magnetic eruption in MAD (I)

Magnetic eruption (ejection of flux rope) strongly perturb B field lines → reconnection

- Test 1: non-axisymmetric distribution of current density



# Driving mechanism of reconnection: Magnetic eruption in MAD (II)

## Test 2: power spectrum analysis

- Fourier transform:

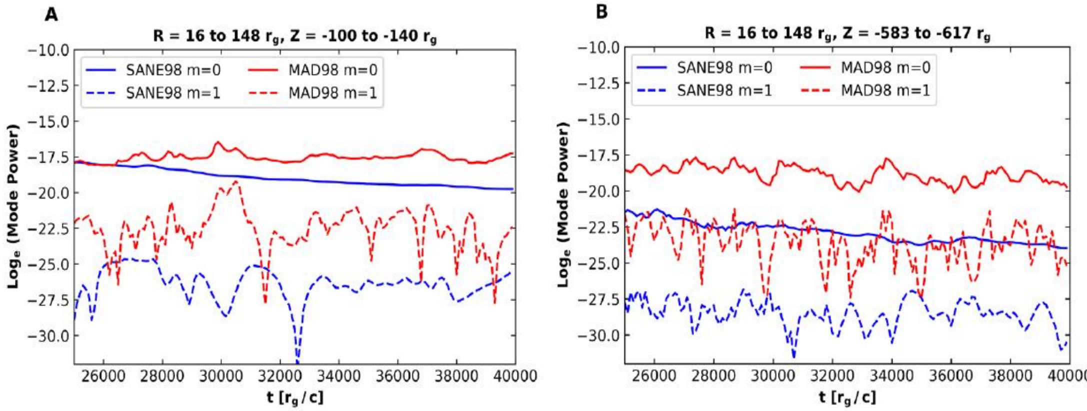
$$f(m,k) = \frac{1}{V_{\rm cl}} \iiint_{V_{\rm cl}} |\mathbf{J}|\, e^{i(m\phi+kz)} r dr d\phi dz$$

- Power spectrum:

$$|f(m,k)|^2 = \{\mathrm{Re}[f(m,k)]\}^2 + \{Im[f(m,k)]\}^2$$

$$\mathrm{Re}[f(m,k)] = \frac{1}{V_{\rm cl}} \iiint_{V_{\rm cl}} |\mathbf{J}| \cos(m\phi + kz) r dr d\phi dz$$

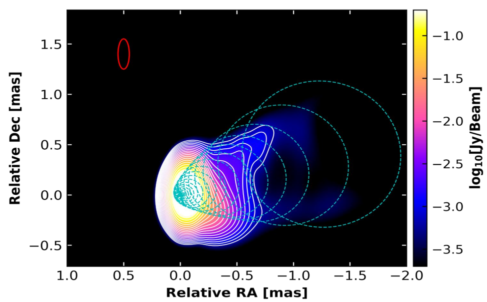
$$Im[f(m,k)] = \frac{1}{V_{\rm cl}} \iiint_{V_{\rm cl}} |\mathbf{J}| \sin(m\phi + kz) r dr d\phi dz$$



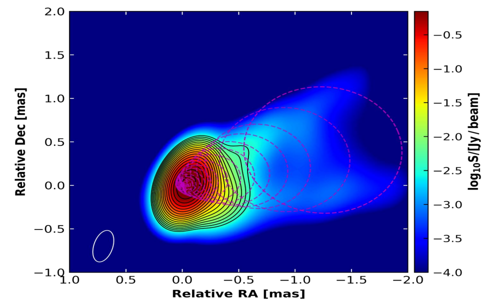

- Conclusions:
  - m=1 power in MAD much larger than SANE
  - Mode power same for small radii (not kink)
  - Variability timescale similar to that of $\phi_B$

# Images by a $N_{pl}/N_{tot}$ = 0.5 test model

86 GHz

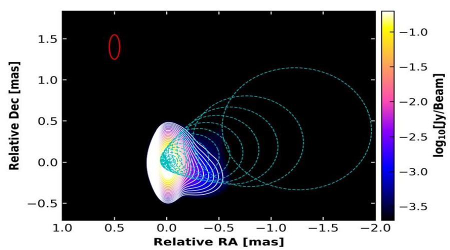


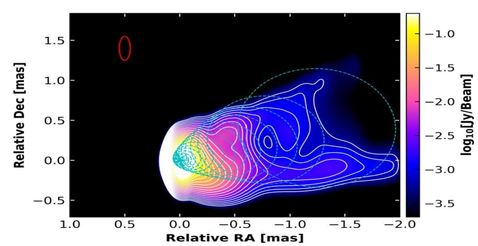

43 GHz



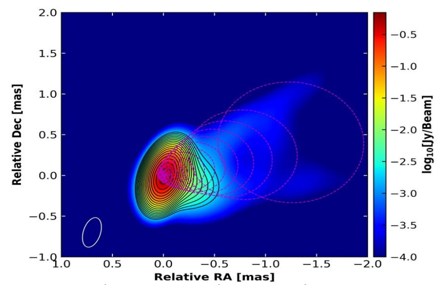

The results are more similar to the thermal-only model:

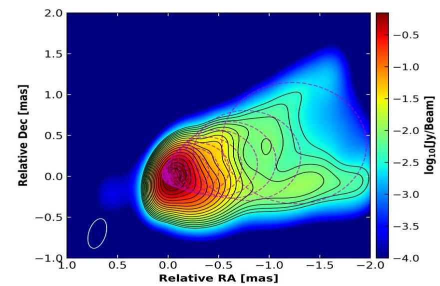
86 GHz




43 GHz



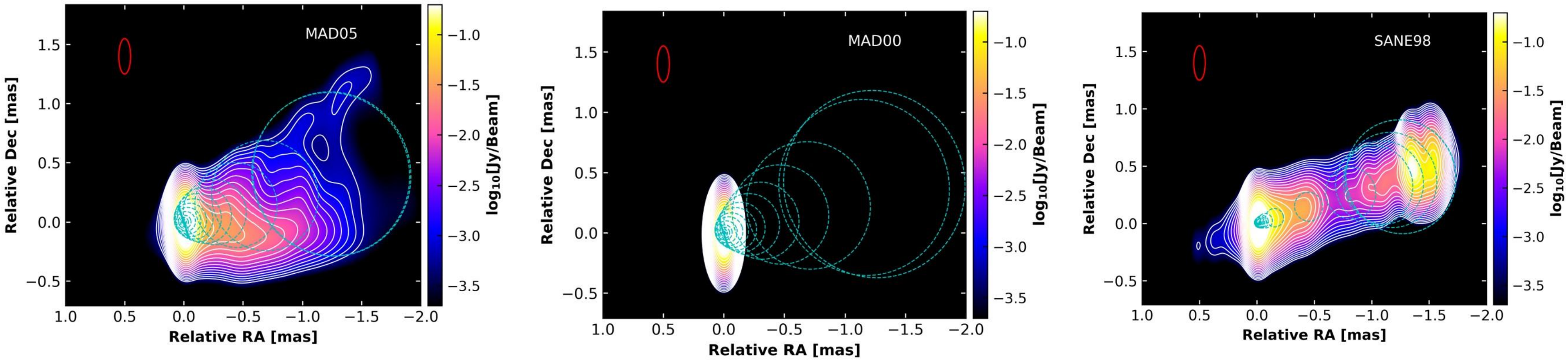




Thermal-only

Fiducial

**Conclusion:**
**Simply adding nonthermal electrons not work!**

# Images predicted by other models

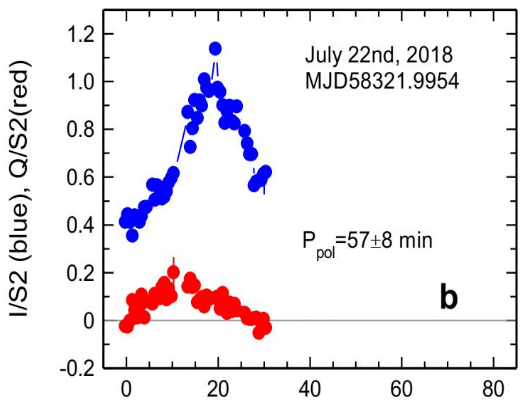


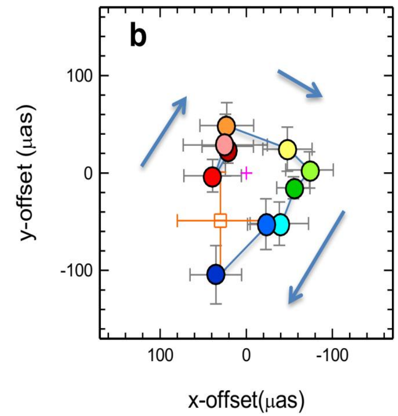

- MAD00:  jet too short
- MAD05&SANE98: no limb-brightening
- SANE98: too narrow
- Physical reason:
  - Spatial distribution of nonthermal electrons is not `correct' (B field configuration)

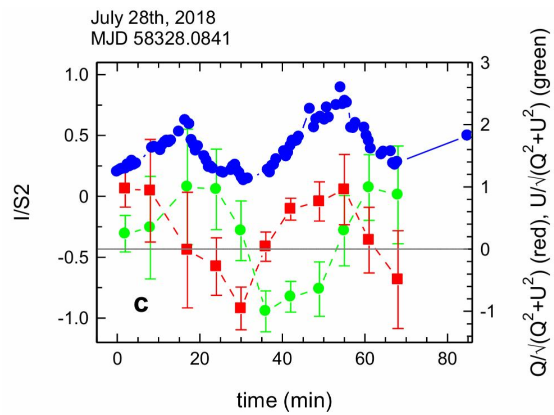
# Modeling flares of Sgr A* based on GRMHD simulations

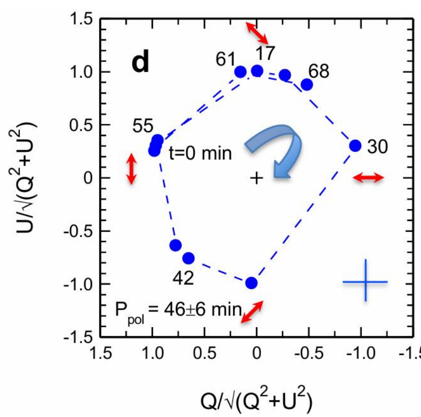
Lin & Yuan 2024, MNRAS

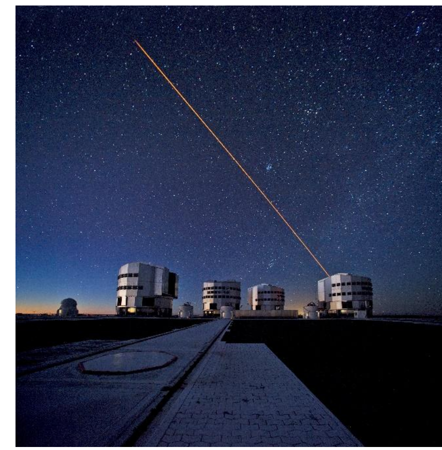
# Flares in Sgr A*: GRAVITY results



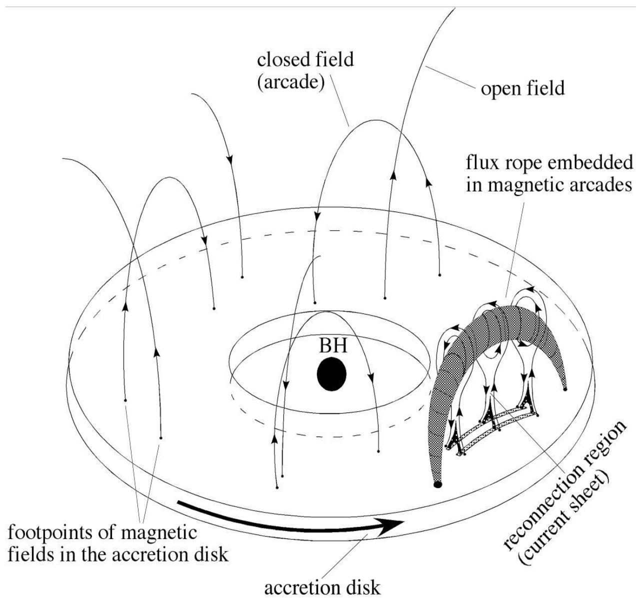



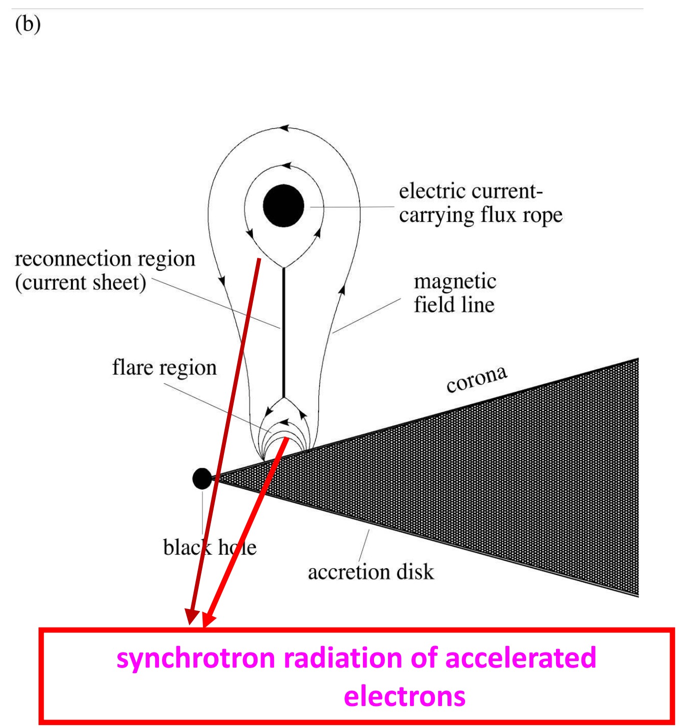



- Projected distance increases with time
- Super Keplerian motion

# An MHD model for flare and ejection

**Yuan, Lin, Wu & Ho 2009**

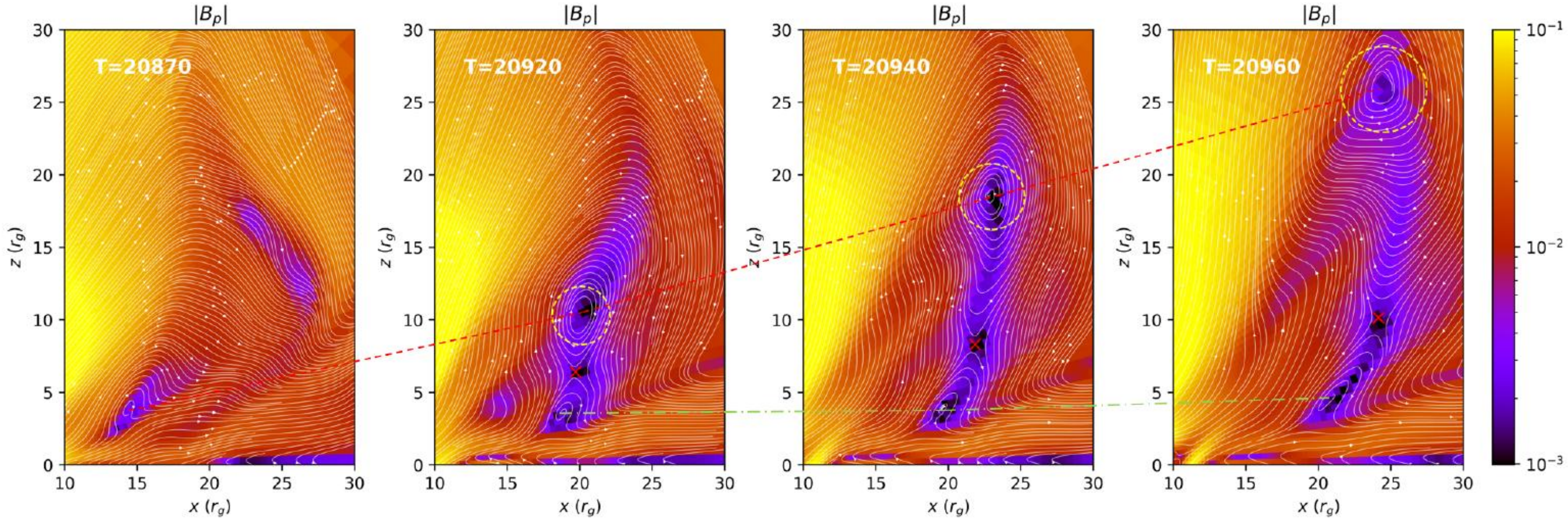



- $B$ field lines emerges out of accretion flow due to Parker instability
- Reconnection occurs due to differential rotation & turbulence
- Formation and ejection of flux rope → magnetic eruption

# Confirmed by 3D GRMHD simulations

**Cemeljic, Yang, FY et al. 2022, ApJ**



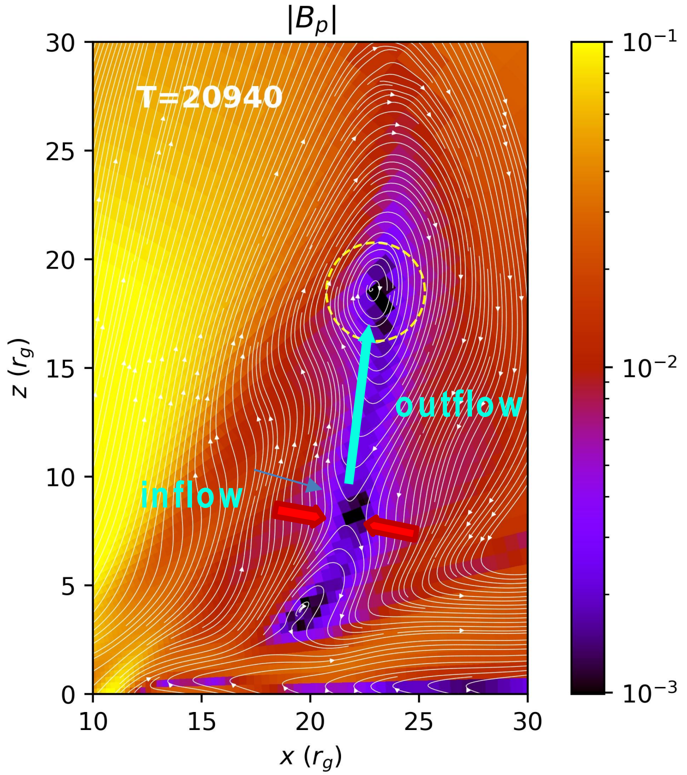

New finding: Formation of flux rope has periodicity

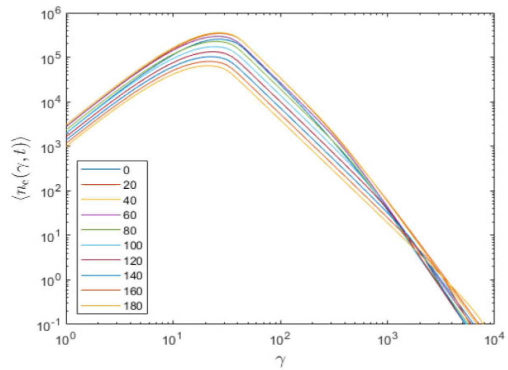
# Determining nonthermal electrons

**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: $Q_{\rm inj} = c\gamma^{-p}, \gamma_{\min} \leq \gamma \leq \gamma_{\max}$
- Solve for the time-dependent energy distribution of nonthermal electrons (radiative & adiabatic cooling):

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

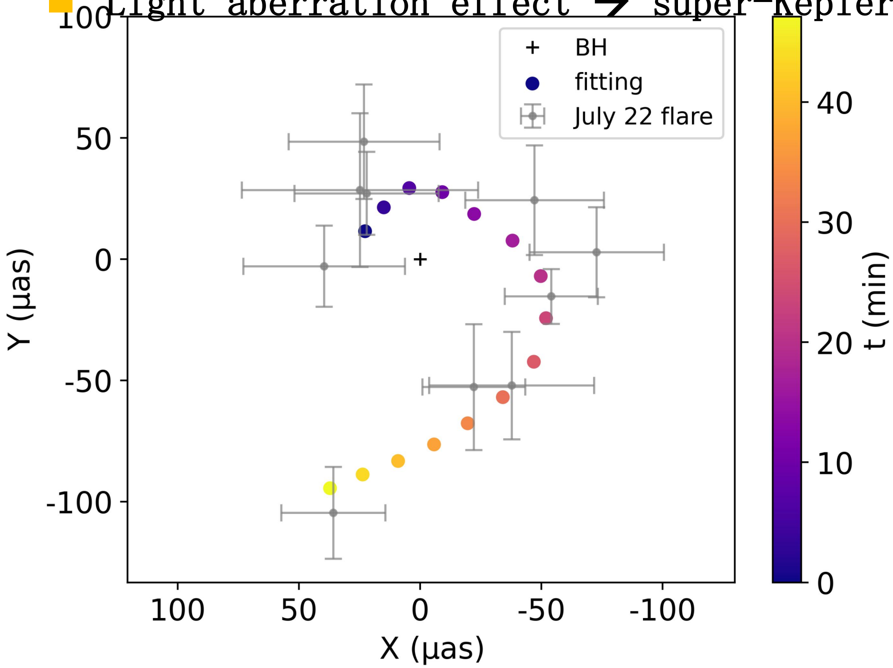


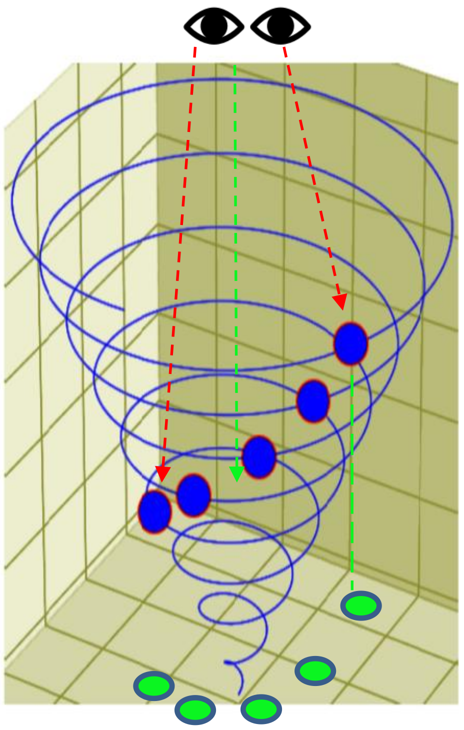



# Results: hot spot trajectory and super-Keplerian motion

**Lin & Yuan 2024, MNRAS**

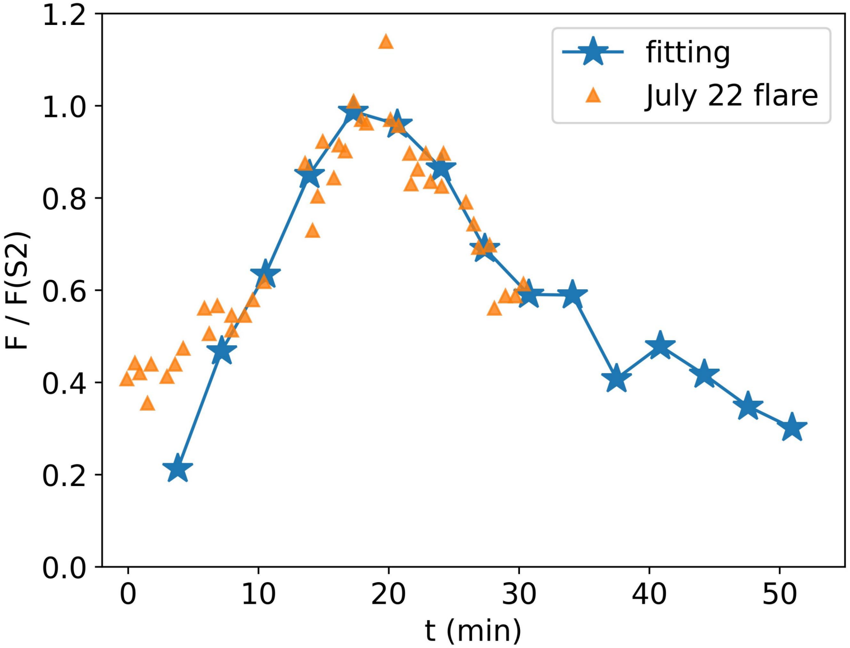
- We directly find a flux rope from simulation data, with trajectory consistent with observation
- Super-Keplerian motion:
  - Rotation of the flux rope is sub-Keplerian
  - But increases to ~0.96 $\Omega_K$ at projected plane
  - Light aberration effect → super-Keplerian

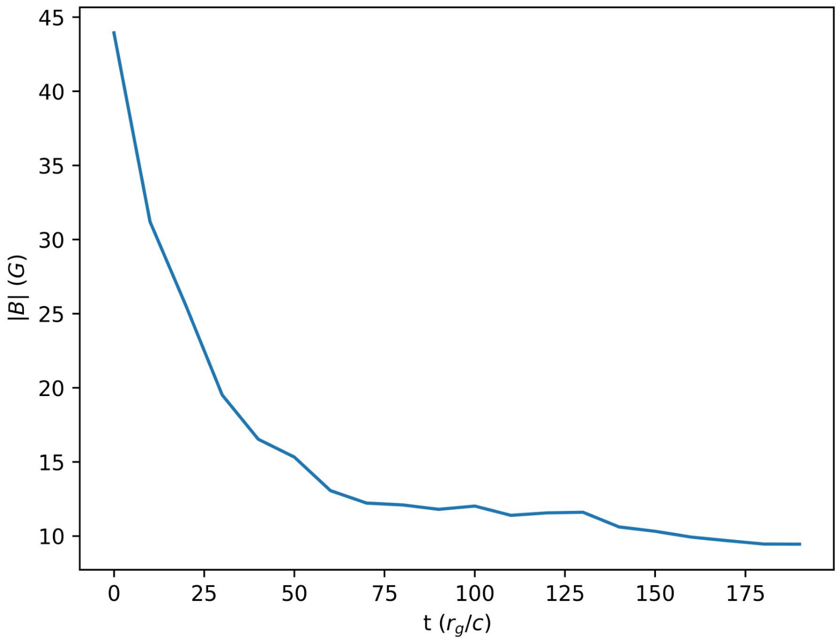


# Light curve

Lin & Yuan 2024, MNRAS

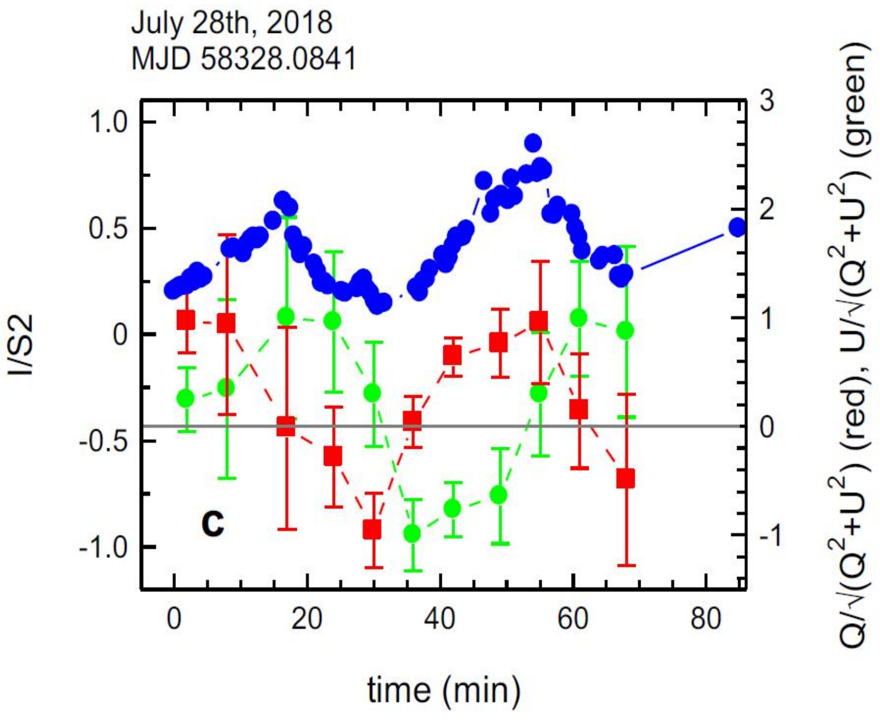


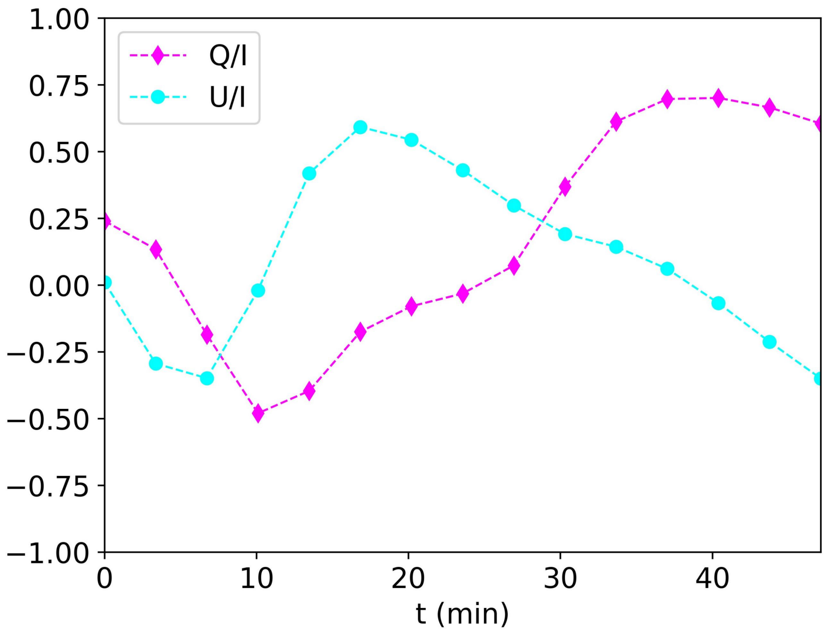




- The rise of the light curve is mainly caused by the injection of the non-thermal electrons
- The decay of the light curve is due to:
  - Decrease of field strength
  - Decrease of the injection power
  - Radiative cooling

# Polarization

**Lin & Yuan 2024, MNRAS**




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

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