Could magnetic reconnection be the source of the Sagittarius A* flares?

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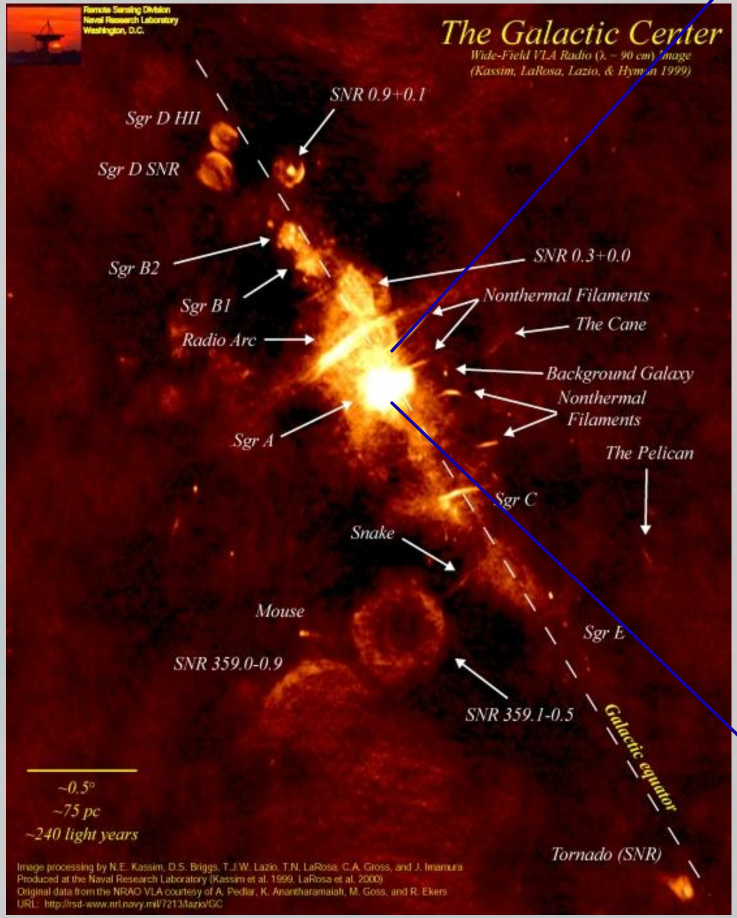
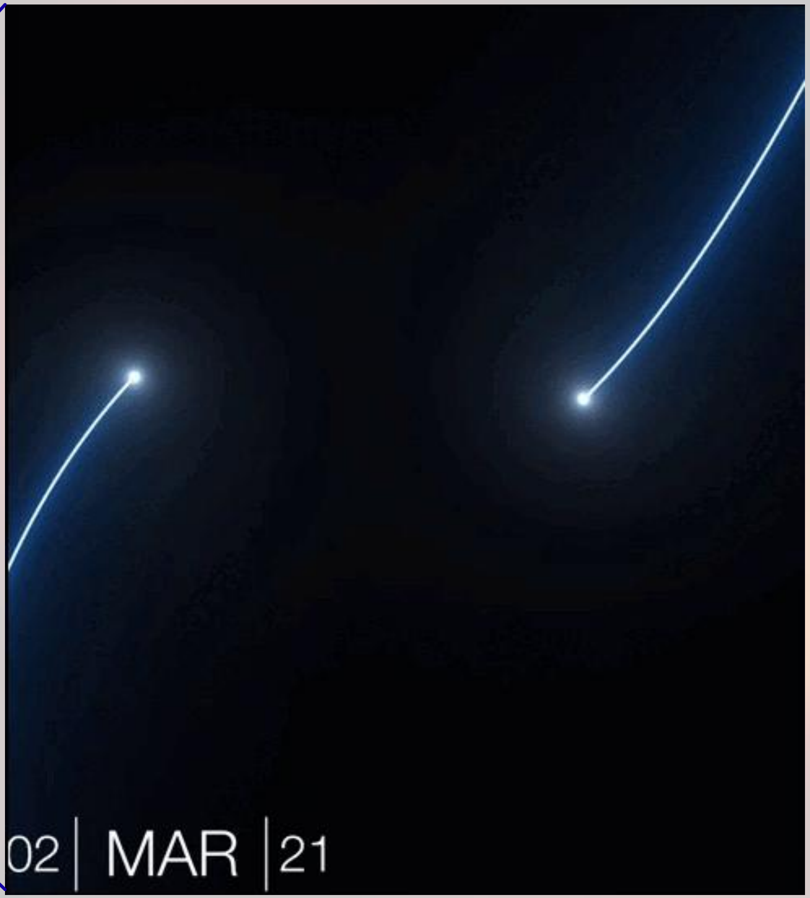
Table of content

1. Introduction
2. Magnetic reconnection in black holes environment
   1) GRMHD simulations
   2) (GR)PIC simulations
3. Hotspot model from magnetic reconnection
   1) Model properties
   2) Comparison with observations
4. Future prospects

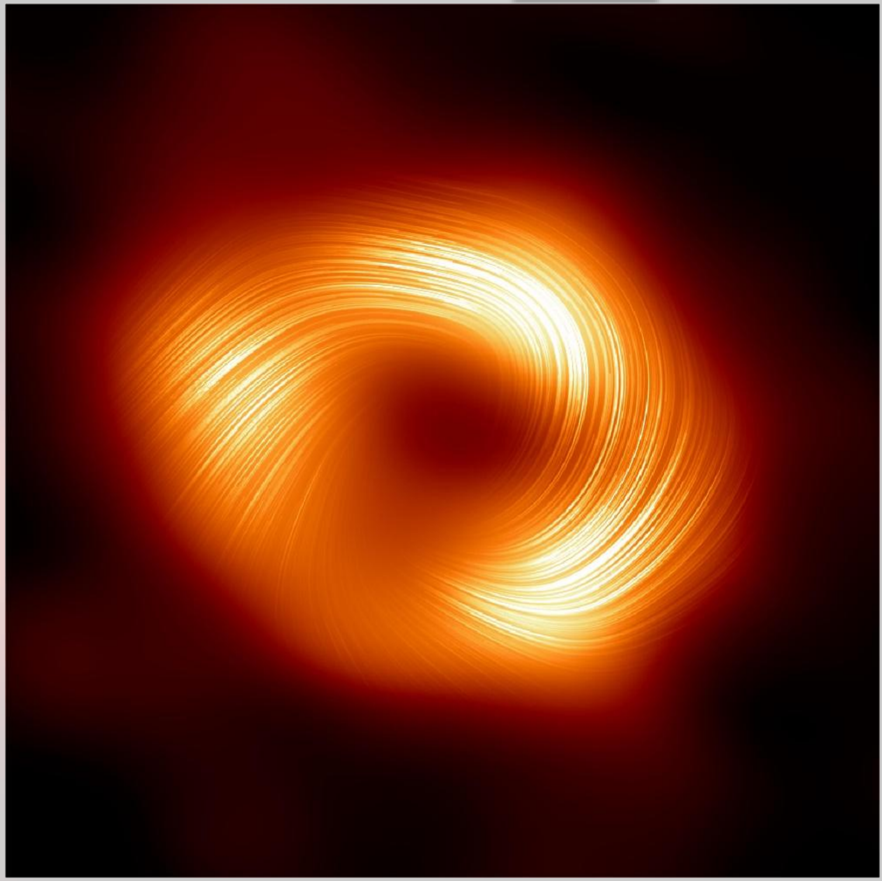
Conclusion

1. Introduction



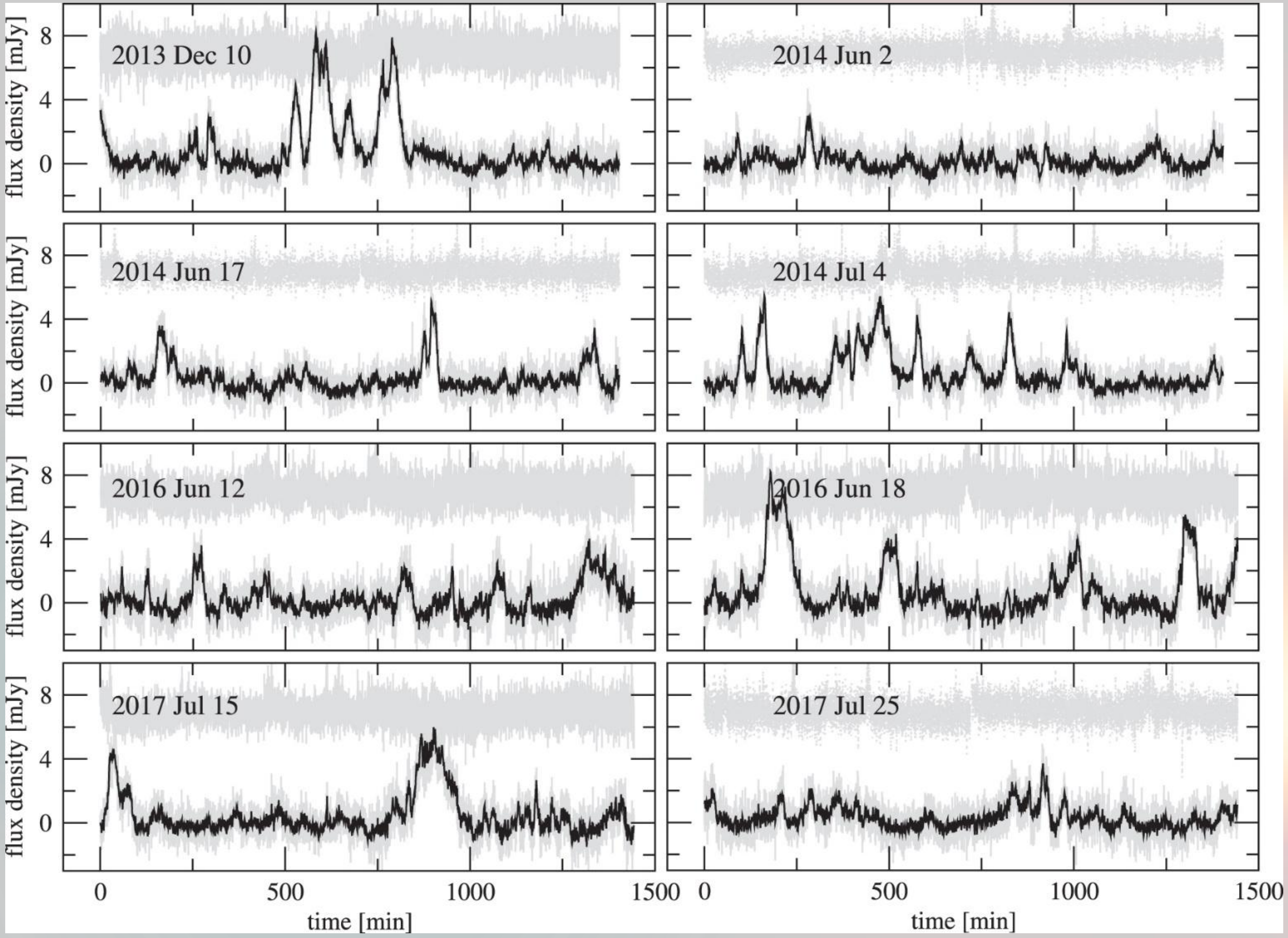


Credits : Naval Research Laboratory & ESO/GRAVITY collaboration

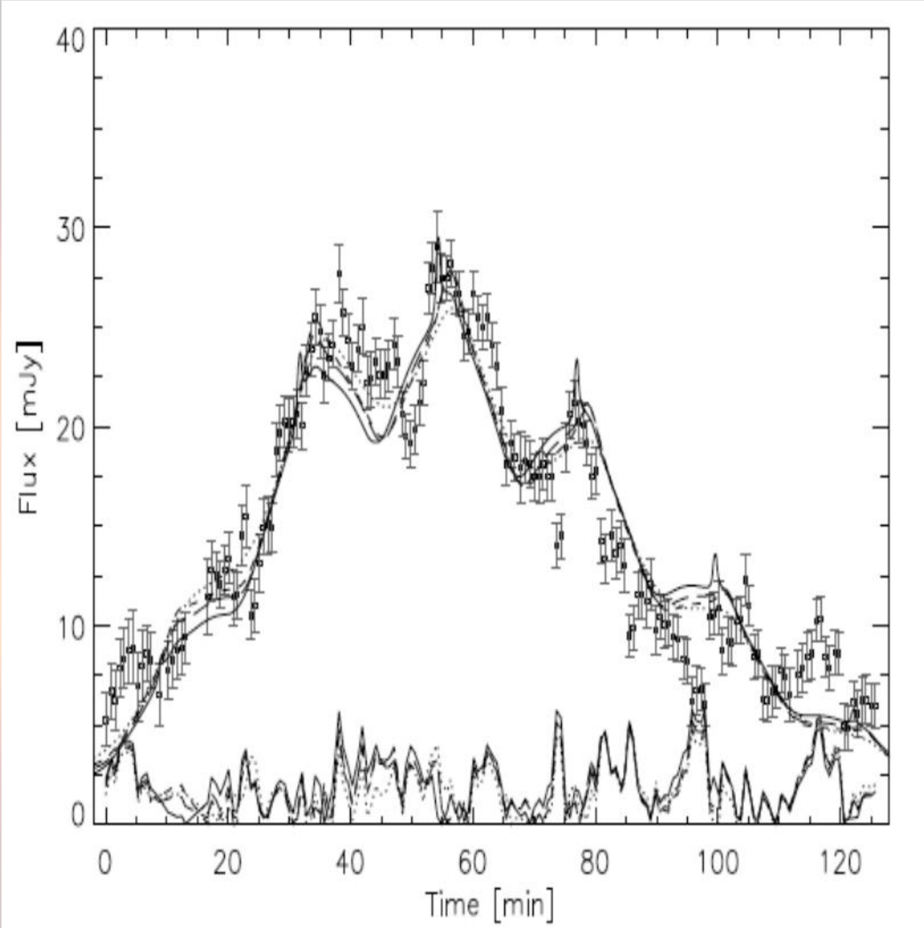


Polarized reconstructed images of Sgr A*. Credits : EHT collaboration

1. Introduction

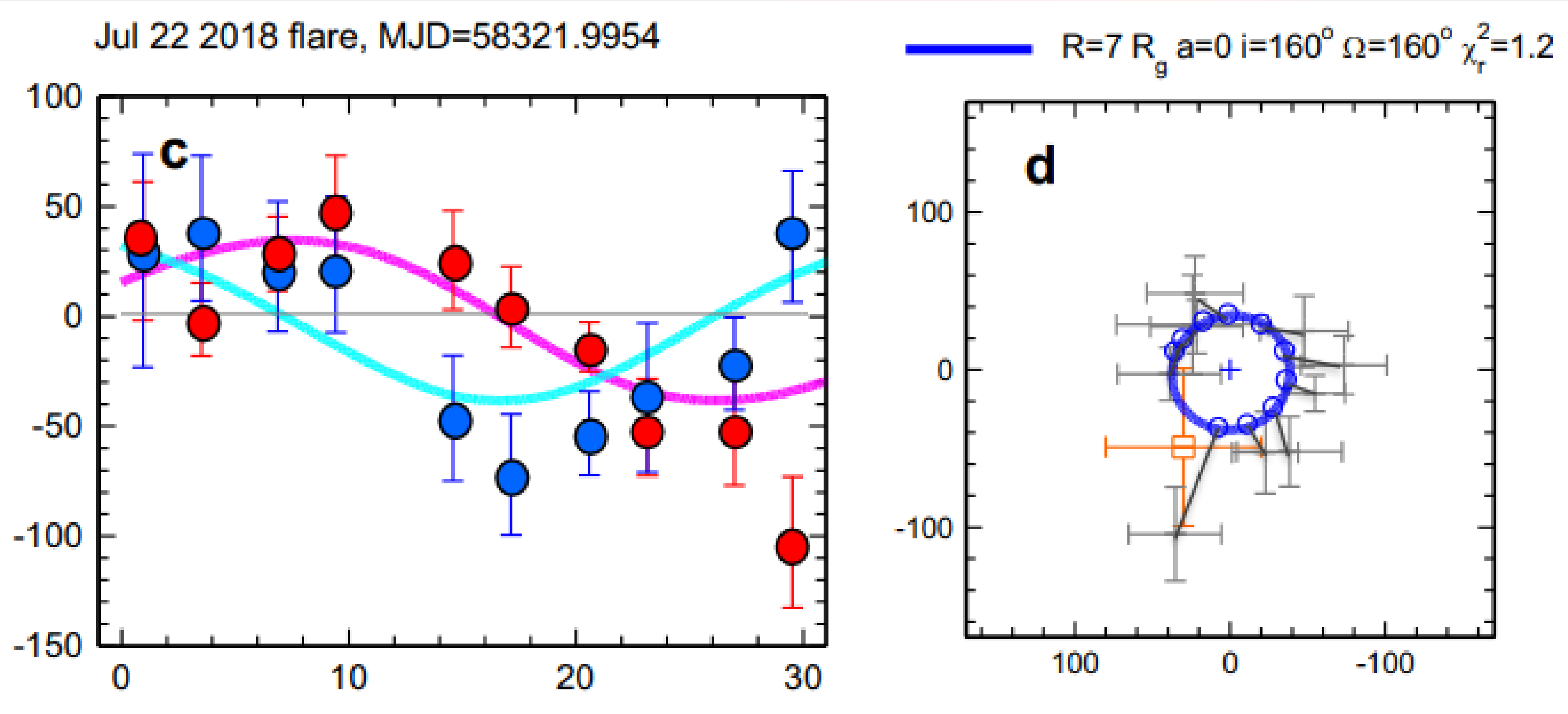


Light curves of Sgr A* in NIR with *Spitzer*. Credit : *Witzel et al., 2018*



Light curve of Sgr A* in IR (bande-L). Credit : *Hamaus et al., 2009*

Sgr A* flare fit from GRAVITY 2018

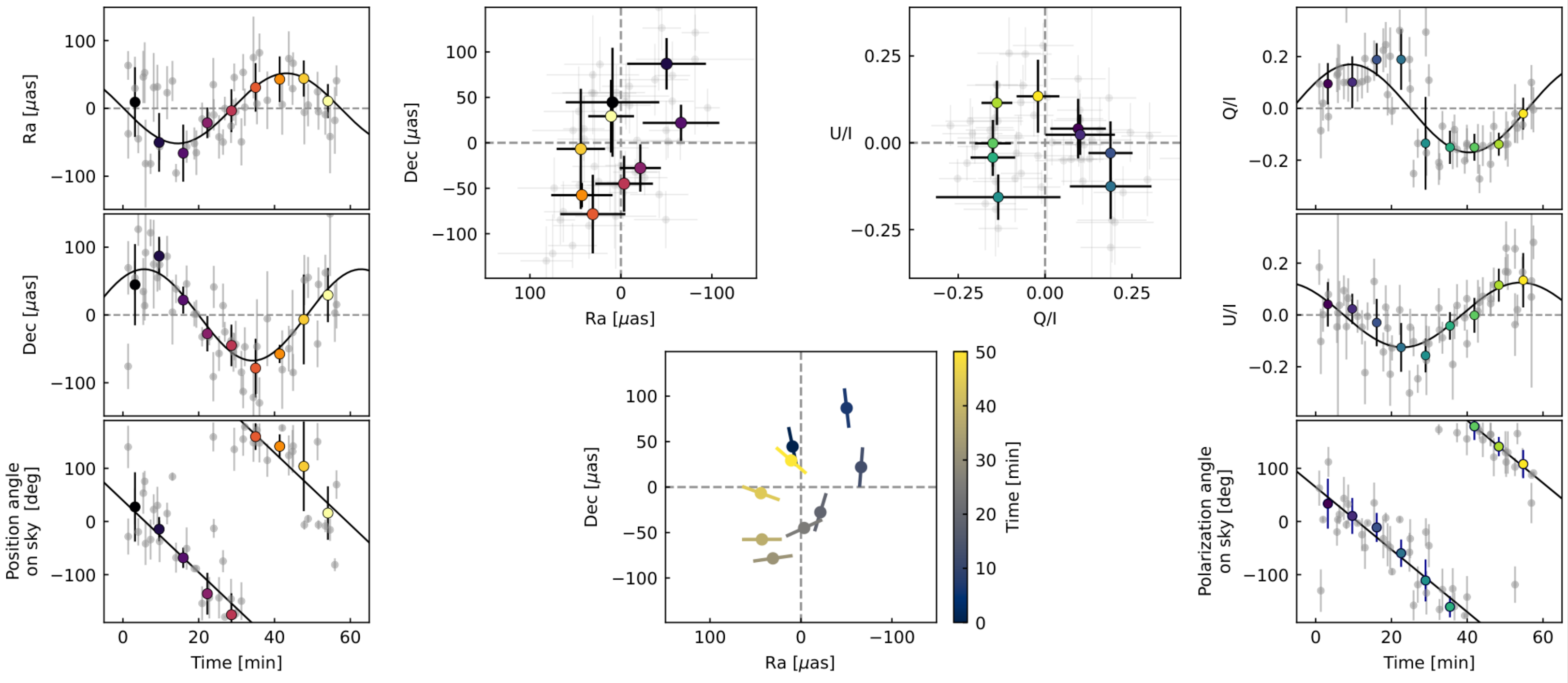


Credit : *GRAVITY Collaboration, 2018*

- Simple hotspot model with a Keplerian circular orbit in the equatorial plane
- Results :
  - **Low inclination**
  - Orbit at **a few** $\boldsymbol{R_g}$
  - Possible **super-keplerian velocity** ?

1. Introduction

Sgr A* flare in NIR

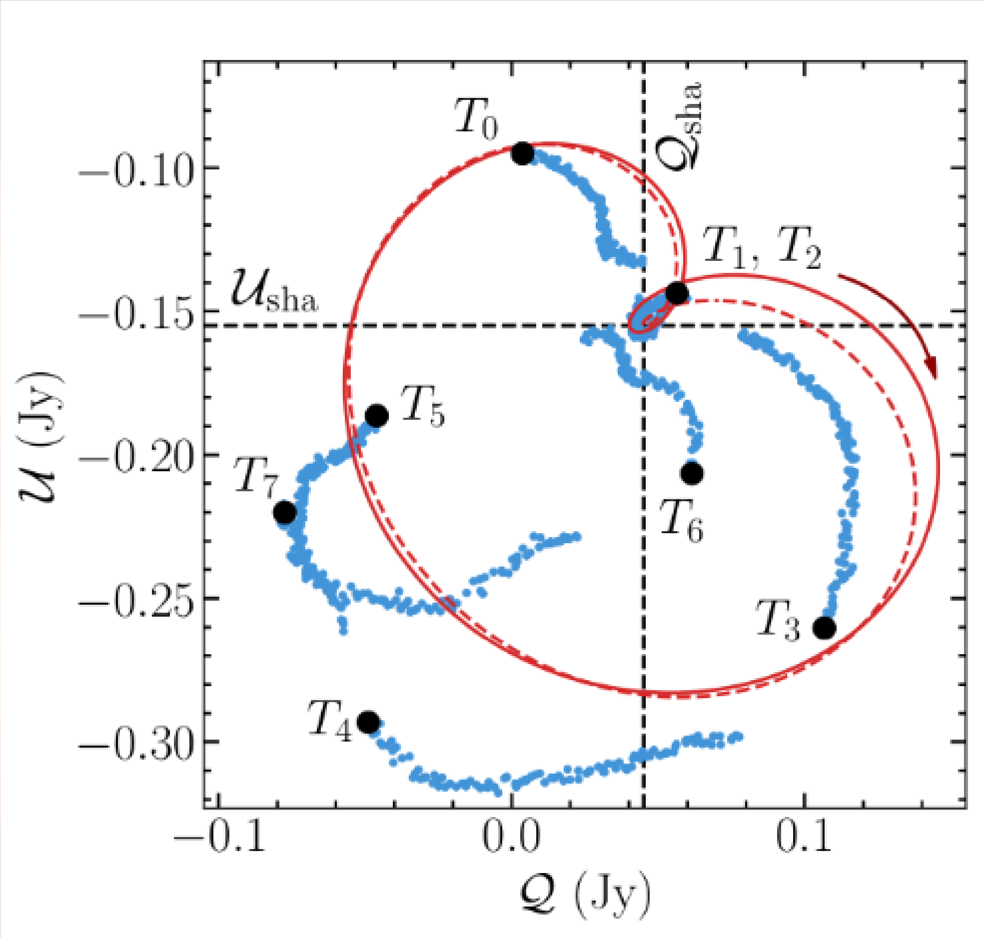


Credit : *GRAVITY Collaboration, 2023*

- Time scale of **30min-1h**
- Average flare shows orbital motion at $\boldsymbol{r = 9M}$ with $\boldsymbol{i \approx 157°}$
- Polarization angular velocity is only compatible with **poloidal magnetic field** configuration
- Maybe **super Keplerian** velocity
- Some **double peak LC** have been observed

Sgr A* flare in radio

- Time scale of ~**70min**
- Polarization loops also hints toward an equatorial orbital motion of an hotspot at $r = 10\mathrm{M}$ and $i = 160°$
- Radio polarization also constraint the **magnetic field** to be in a **purely vertical** configuration
- Orbital velocity is **Keplerian**
- Very low density plasma $n_e \approx 5 \times 10^5\ cm^{-3}$

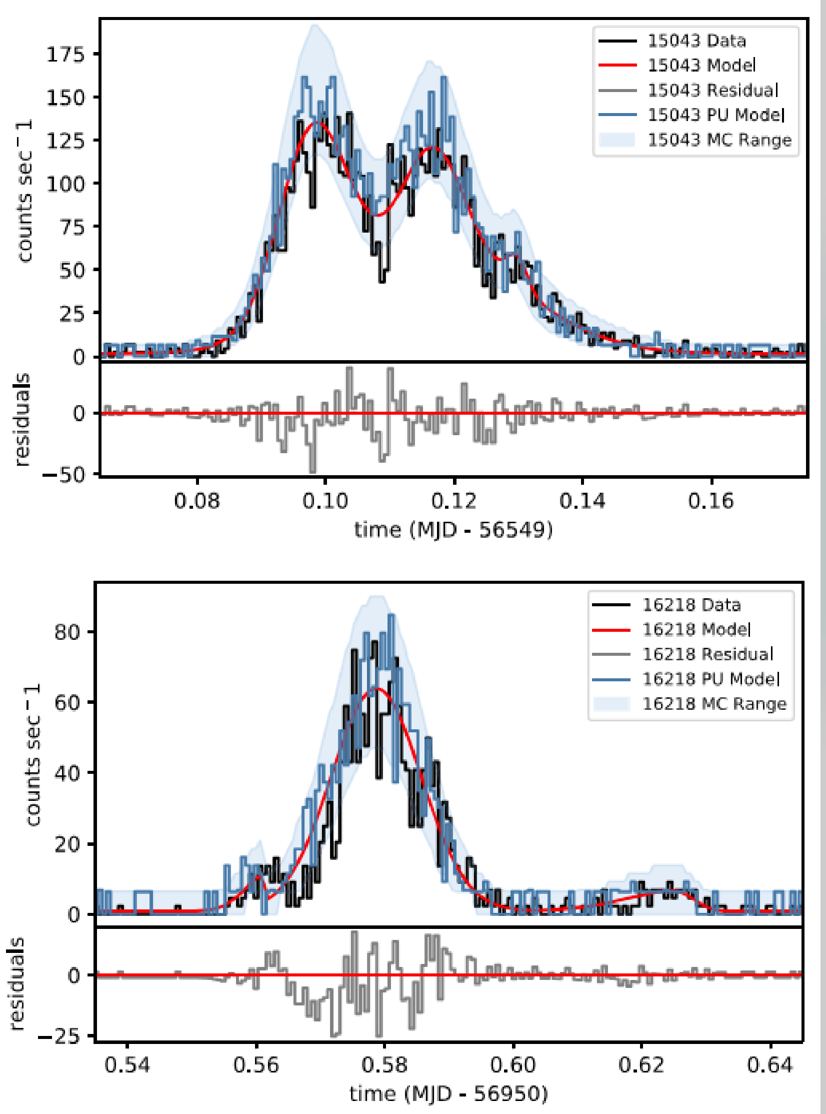


Credit : *Wielgus et al., 2022*

1. Introduction

Sgr A* flare in X-rays

- **Single** and **double peak** light curve are observed
- Time scale between **~10min** and **1,5h**
- Hard spectral index $\boldsymbol{\Gamma \approx 2,0}$
- High energy photons could be generated by
  - High energy (**non-thermal**) electrons emitting **synchrotron** radiation
  - Low energy electrons emitting **synchrotron self-Compton (SSC)** radiation

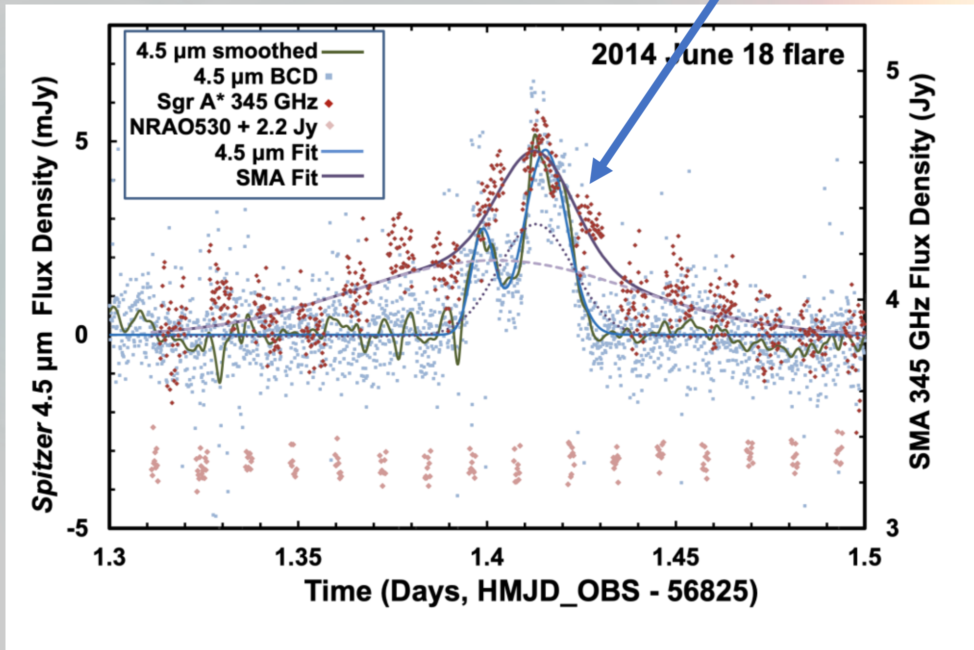


Credit : *Haggard et al., 2019*

1. Introduction

Multi-wavelength Sgr A* flares observation show puzzling properties

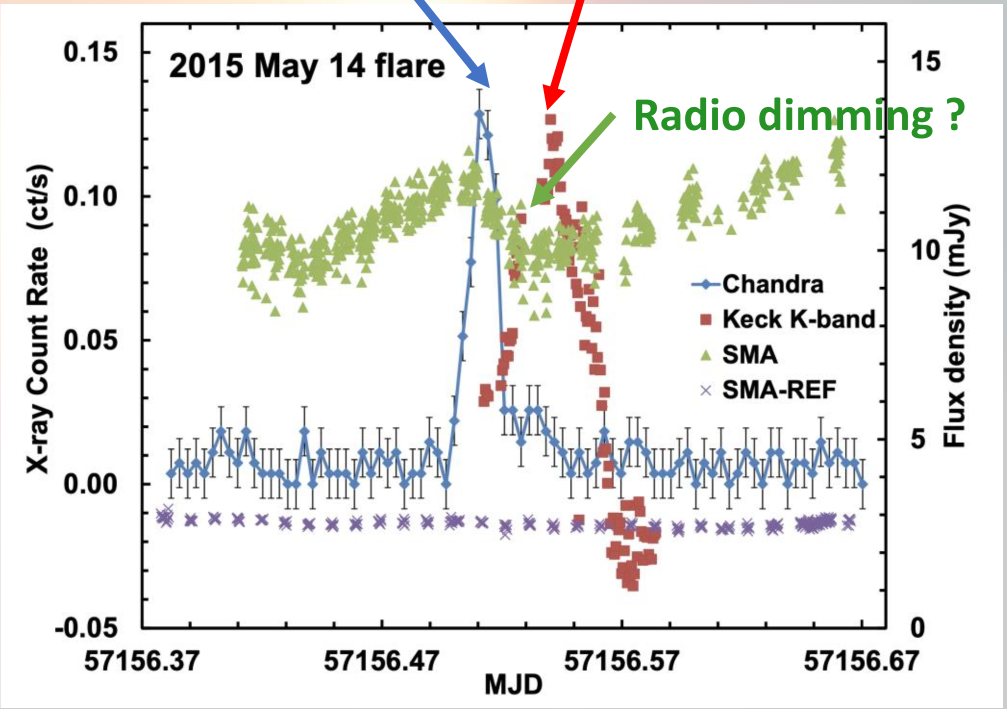
Simultaneous radio and NIR flares



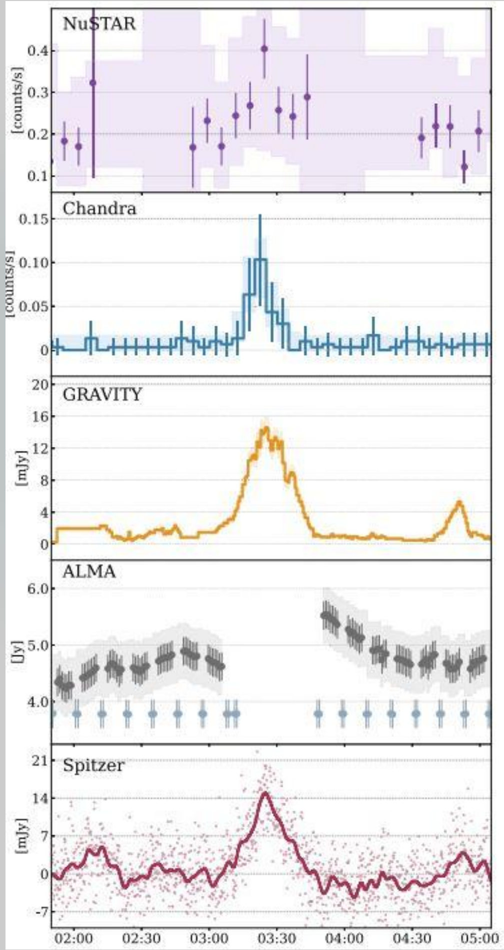
X-ray flare

Delayed flare in NIR

Radio dimming ?



Credit : *Fazio et al., 2018*

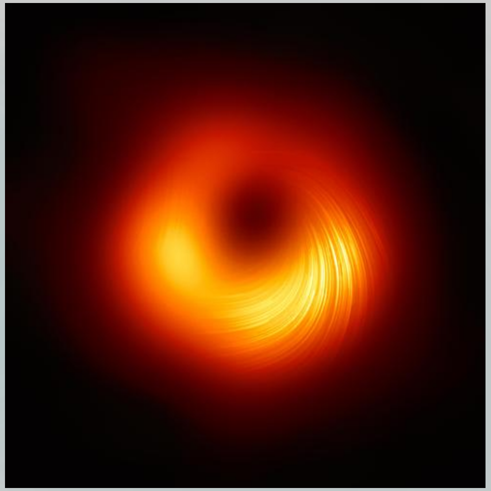


Credit : *Boyce et al., 2022*

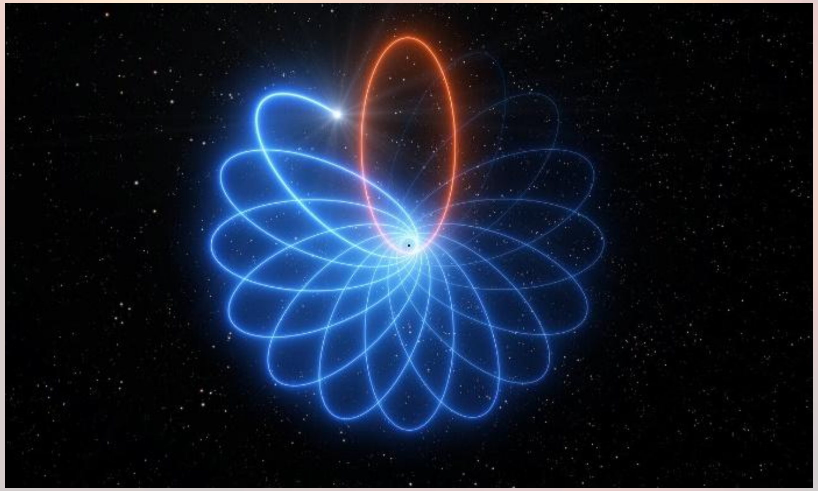
1. Introduction

Long terms objectives:

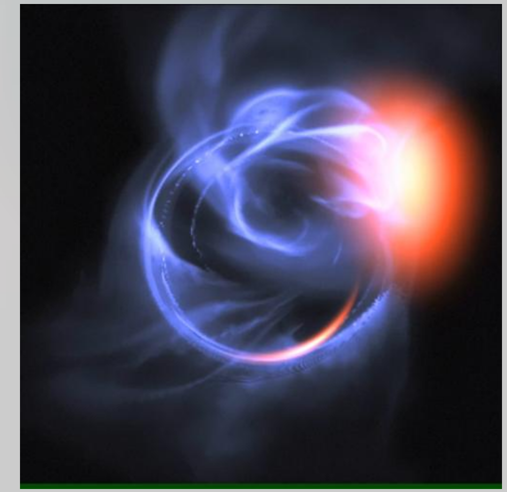
- Test the “no hair” theorem of black holes
- Find a limit of General relativity



Credit : *EHT Collaboration*



Credit : *ESO/L. Calçada*

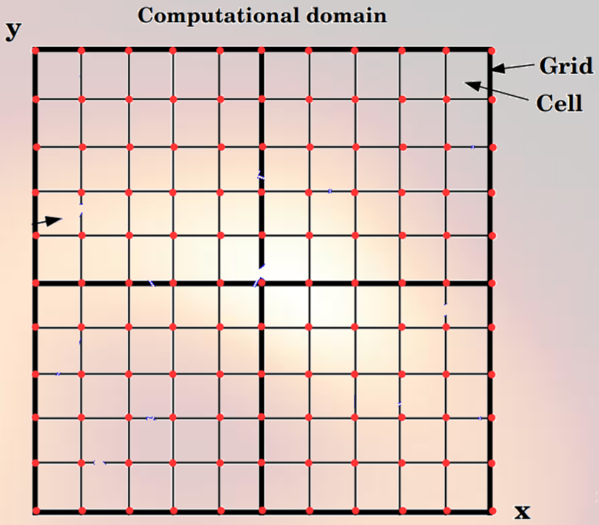


Credit : *ESO/Gravity Consortium*

1. Introduction

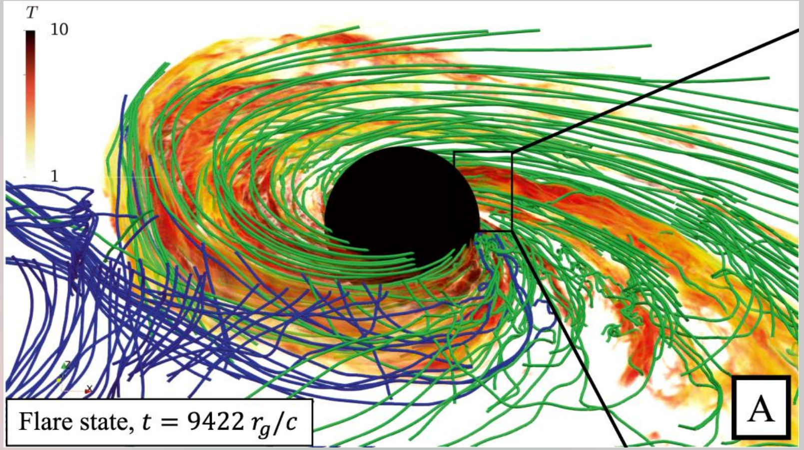
Credit : *National Science Foundation*

Particles-in-Cells (PIC)



Credit : *B. Cerutti*

MagnetoHydroDynamic (MHD)



Credit : *B. Ripperda, 2022*

Short terms objectives :

- Better constrain plasma physics in the strong gravity regime
- Decipher the origin of Sgr A* flares
- Create a model capable of explaining the astrometry, light curves and polarization observables of flares

2. Magnetic reconnection in BH environments

1) GRMHD simulations

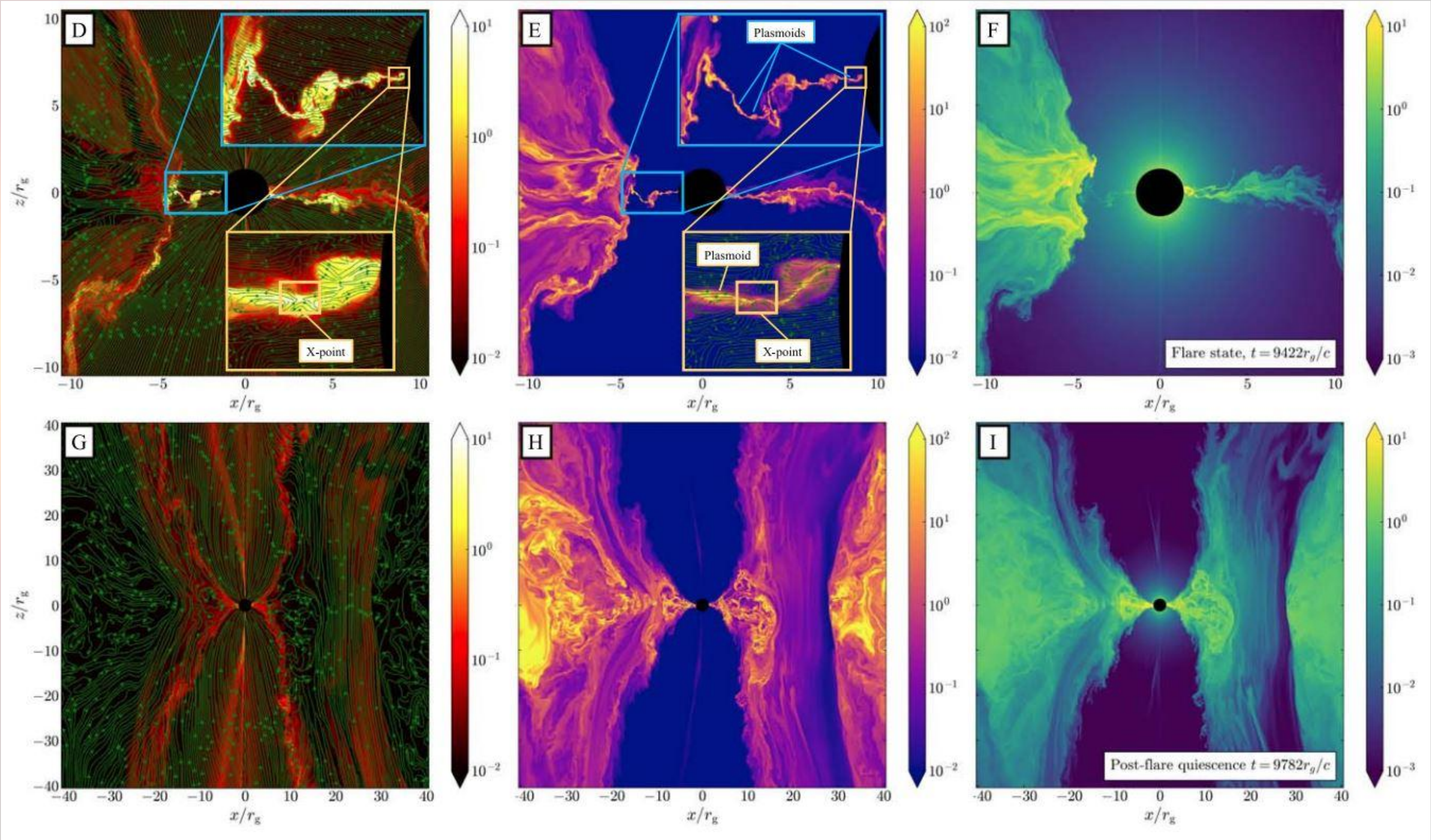
<u>GRMHD simulations :</u>

Pro :

- **Fluid approach** -> reduced number of variables (density, velocity, energy, magnetic field)
- **Large-scale** evolution
- **Long-term** simulations

Cons :

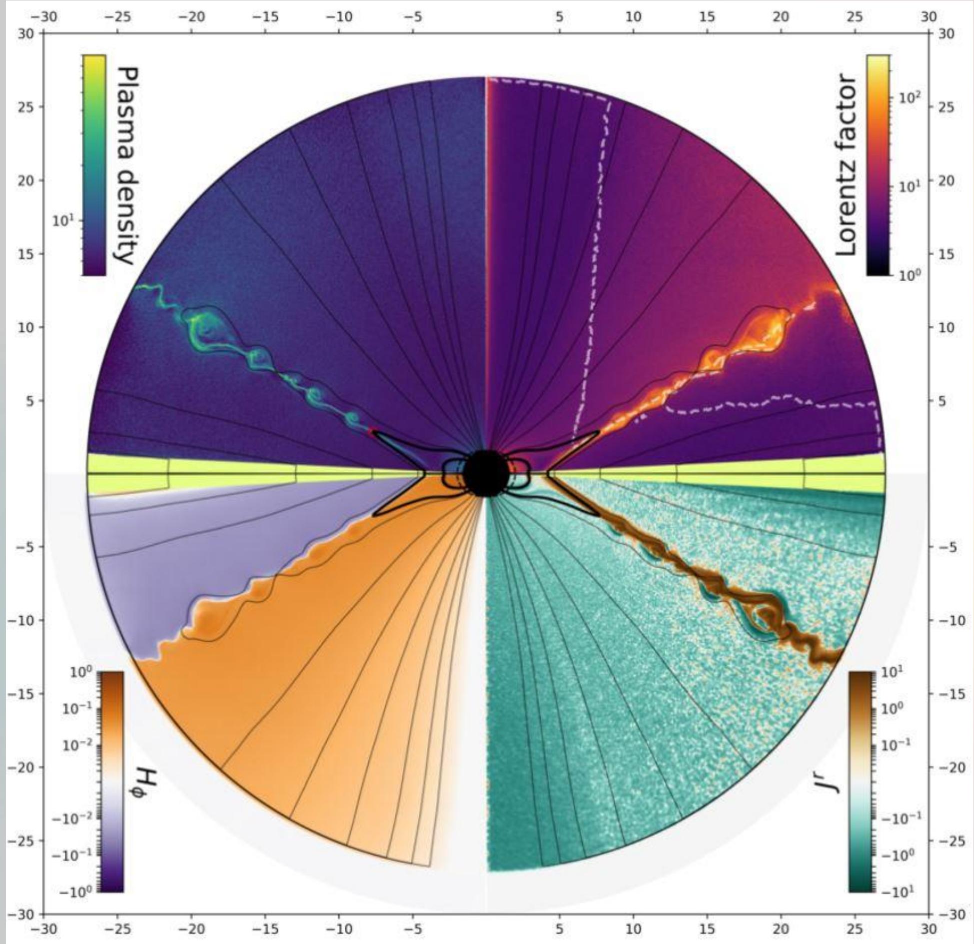
- Fluid approach-> **non** valid for **collisionless plasma**
- **No microphysics**



Credit : *Ripperda et al., 2022*

2. Magnetic reconnection in BH environments

2) (GR)PIC simulations



Credit : *El Mellah et al., 2022*

GRPIC simulations :

Pro :

- Capture all the **microphysics**
- Evolution of the particles **distribution function** and of the electromagnetic field
- Self-consistent **pair production**

Cons :

- **Computationally expensive:** limited number of particles
- **Scale separation**
- **No global** kinetic evolution of the accretion disk

What could we learn from magnetic reconnection simulations ?

- Creation of magnetic island called ***flux tubes*** (both GRMHD and GRPIC)
- Flux tubes **geometry** (both GRMHD and GRPIC)
- **Dynamics** of flux tubes (both GRMHD and GRPIC)
- **Magnetic field configuration** (both GRMHD and GRPIC)
- **Timescales**: duration of flares, delay between two events (GRMHD)
- **Electron Energy Distribution** (EED) **evolution** inside the flux tubes (GRPIC)

3. Hotspot model from MR

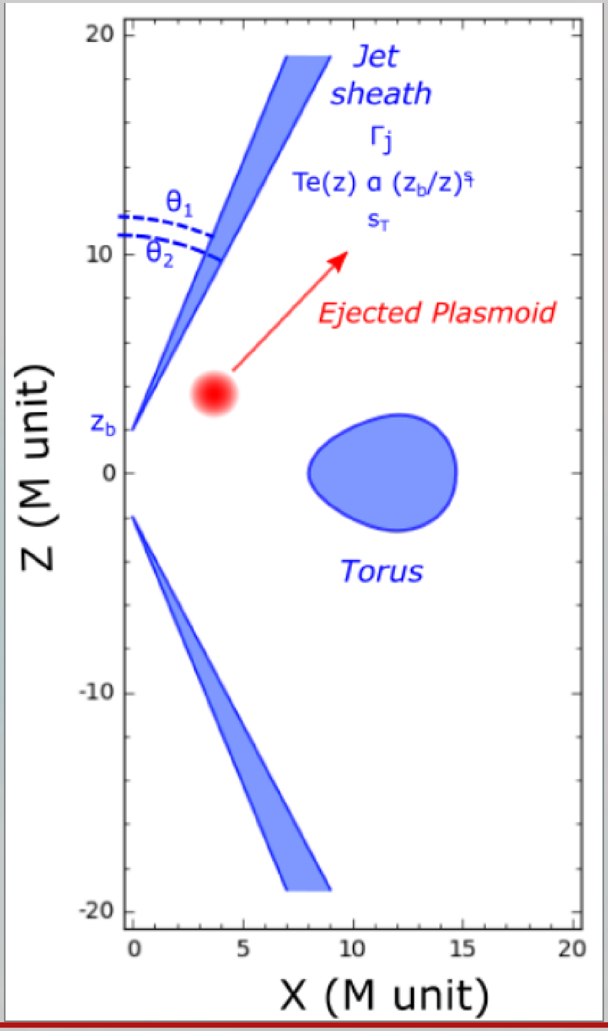
1) Model properties

How build a model from magnetic reconnection simulations?

- Size, shape
- **Motion**
- Number density, temperature, magnetic field and their **profiles** (uniform or Gaussian)
- **Electron distribution function** (thermal, power-law, kappa, …)
- **Magnetic field configuration** (important for polarization)

3. Hotspot model from MR

1) Model properties



Model composed of :

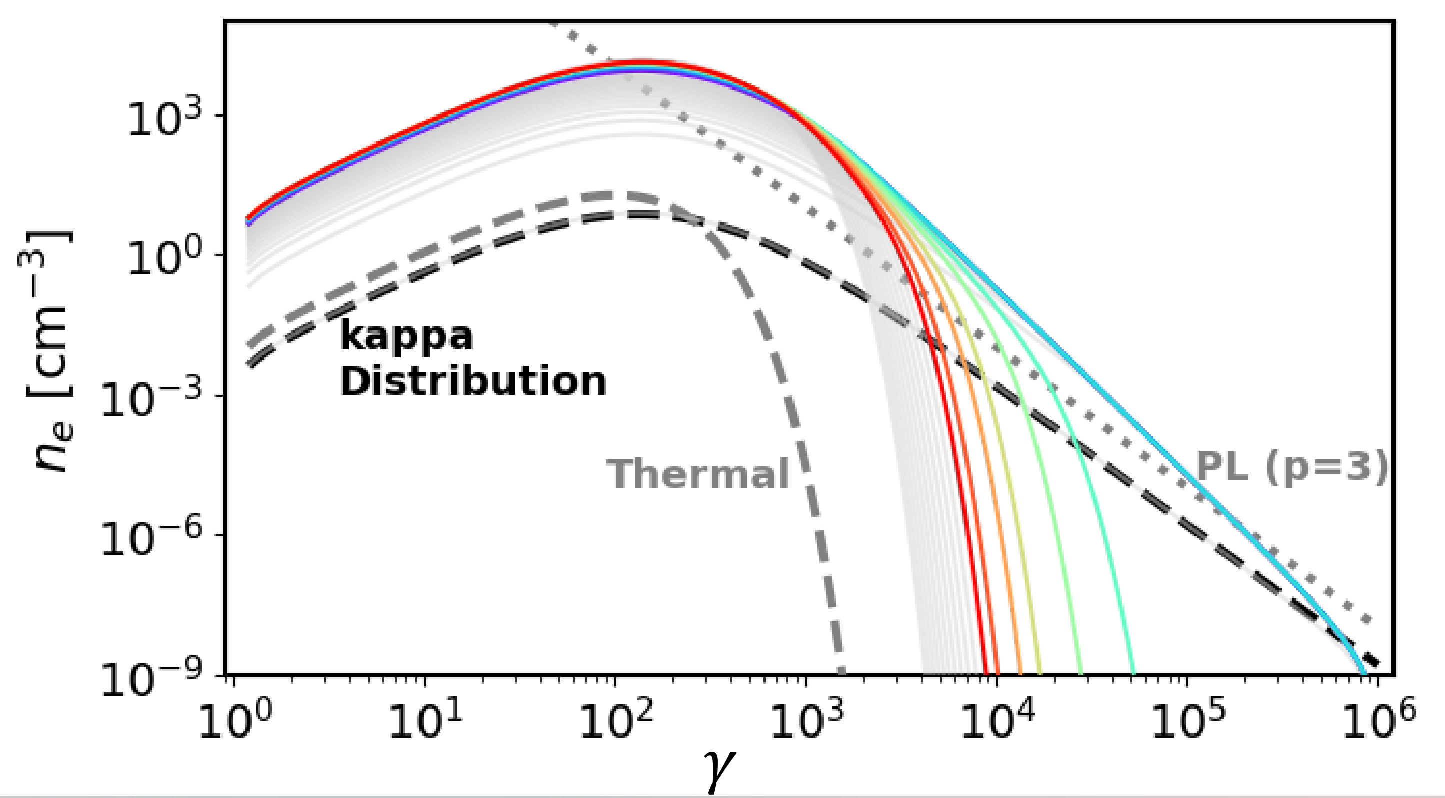
- A **jet** ⟺ quiescent state
- A **hotspot** ⟺ source of the flare

Hotspot :

- Uniform sphere
- Conical ejection, i.e. $v_r > 0$, at $\theta = cst$
- v_φ is a **free parameter** (not necessary Keplerian)
- **Time dependant** electron energy distribution
- Tangled magnetic field (work in progress for Vertical configuration)

3. Hotspot model from MR

1) Model properties



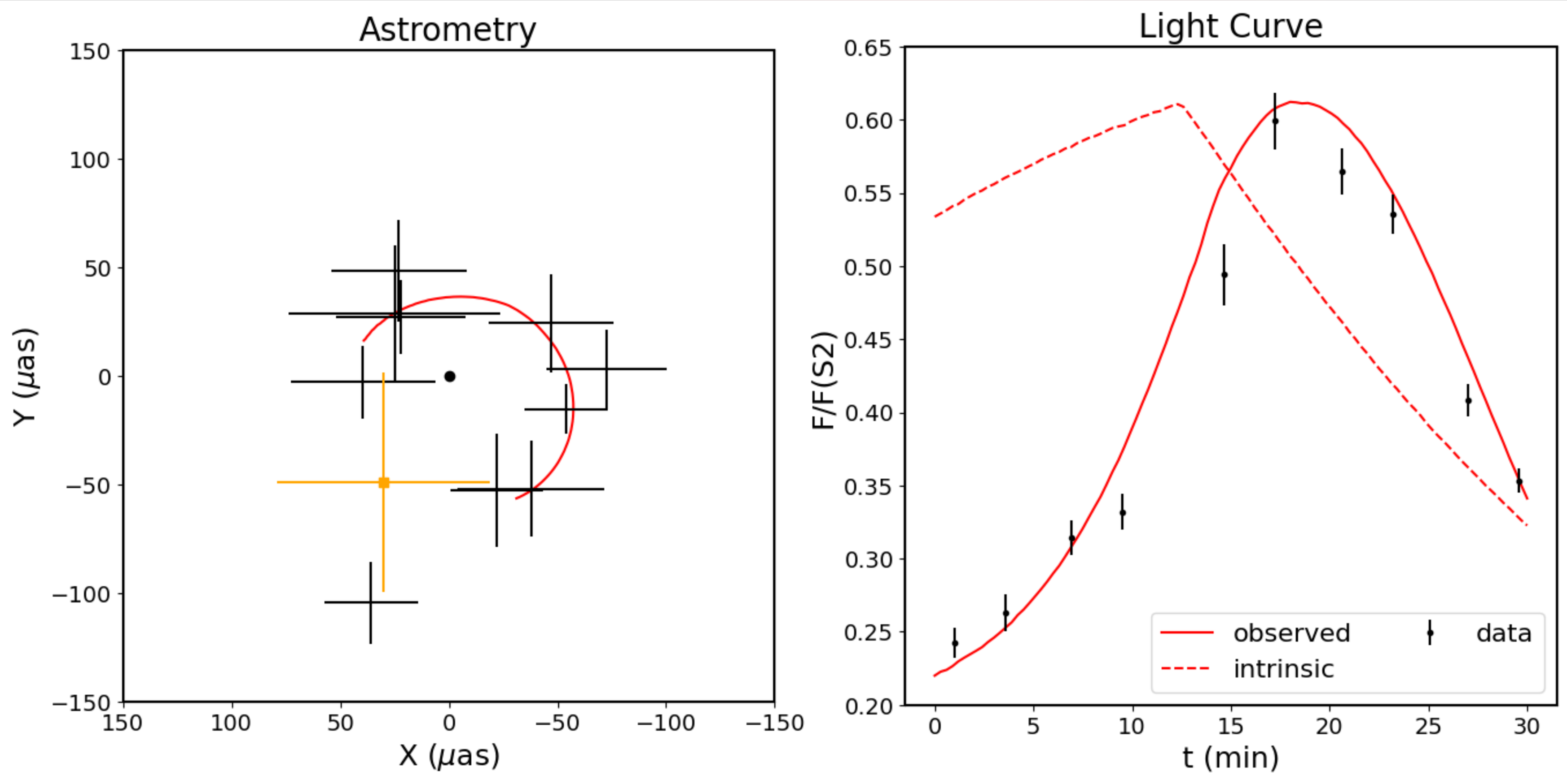
Aimar et al., 2023

2 phases in a kinetic approach (A. Dmytriiev):

- **Growth phase** : injection of accelerated e^- following a κ-distribution at a constant rate
- **Cooling phase** : cooling through synchrotron radiation

3. Hotspot model from MR

2) Comparison with observations



Aimar et al., 2023

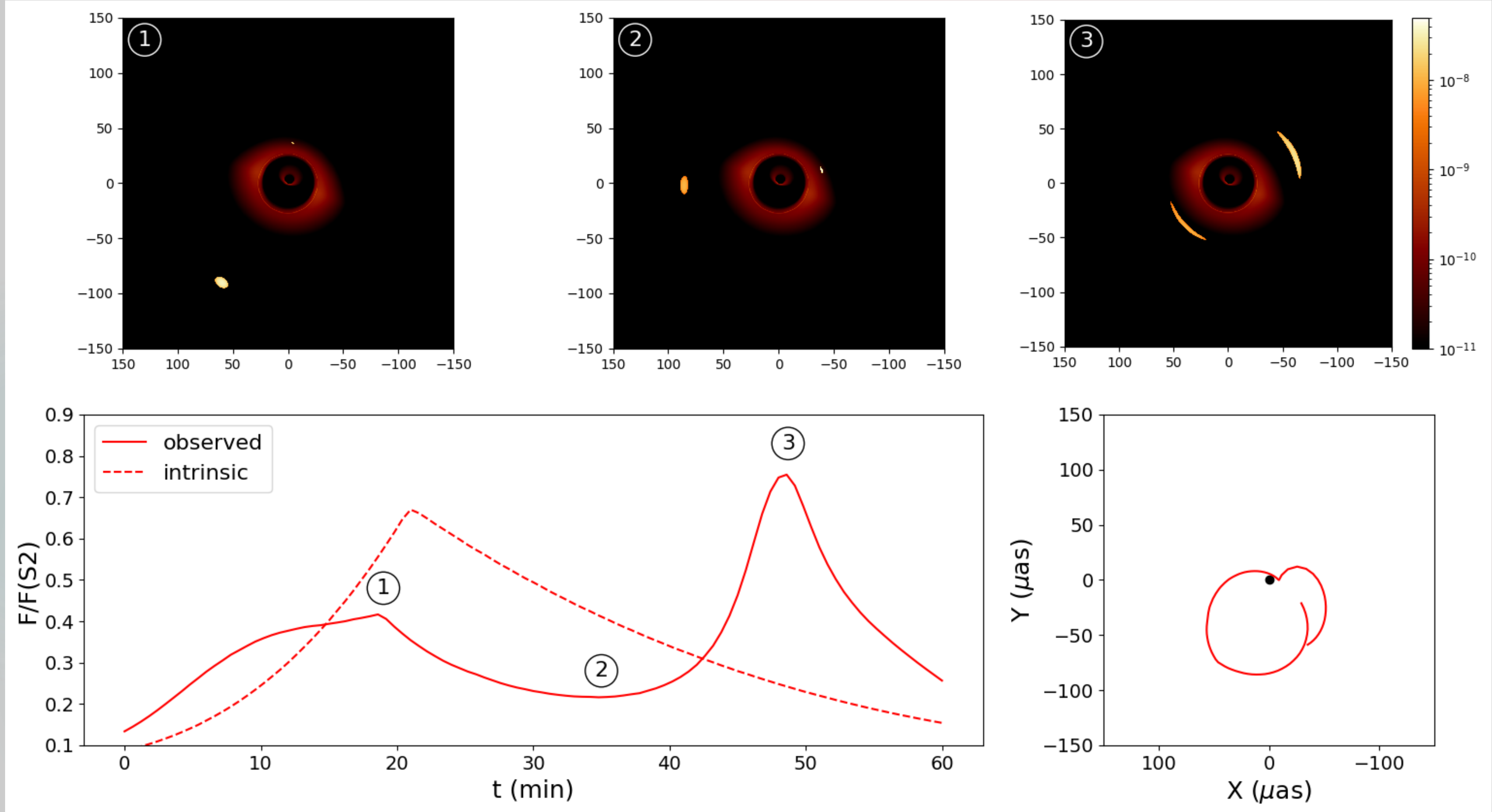
Total number parameters of the hotspot model : 13

22 July flare comparison :

- **Orbital velocity compatible** with constrains from El Mellah et al., 2022
- Strong influence of the **beaming** effect
- Shows good agreement with the data (**not a fit !**)

3. Hotspot model from MR

2) Comparison with observations



Double peak light curve :

- **1st peak** : injection of accelerated electrons
- **2nd peak** : beaming + lensing
  - $\theta \approx$ inclination
  - Plasmoïd is behind the black hole

The alignment constrains the maximum and shape of the second peak

4. Future prospects

Improve the model:

- Better **orbital motion** prescription (work in progress)
- Use **well-defined** magnetic field **configuration** (work in progress)
- Compute **polarized coefficients** from non-well-defined EED (work in progress)
- Study the **multi-wavelength** properties (future work)
- **Fit** the model to data (future work)

Conclusion

- Sagittarius A* flares is an ideal subject for **testing general relativity** and the black hole **no hair theorem**.
- But the physical origin of flares is still under debate. Nevertheless, magnetic reconnection is very promising to explain Sgr A* flares origin.
- We have developed a **hotspot** model using kinetic simulations mimicking magnetic reconnection based on GRMHD and (GR)PIC results. The hotspot model shows very promising results compared to data.
- Next steps : fit the data, include the **polarization** and make a **multi-wavelength** analysis.