



Non-thermal flares and hot spots around Sgr A*

A plasmoid origin



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IPAG - CNRS → USACH



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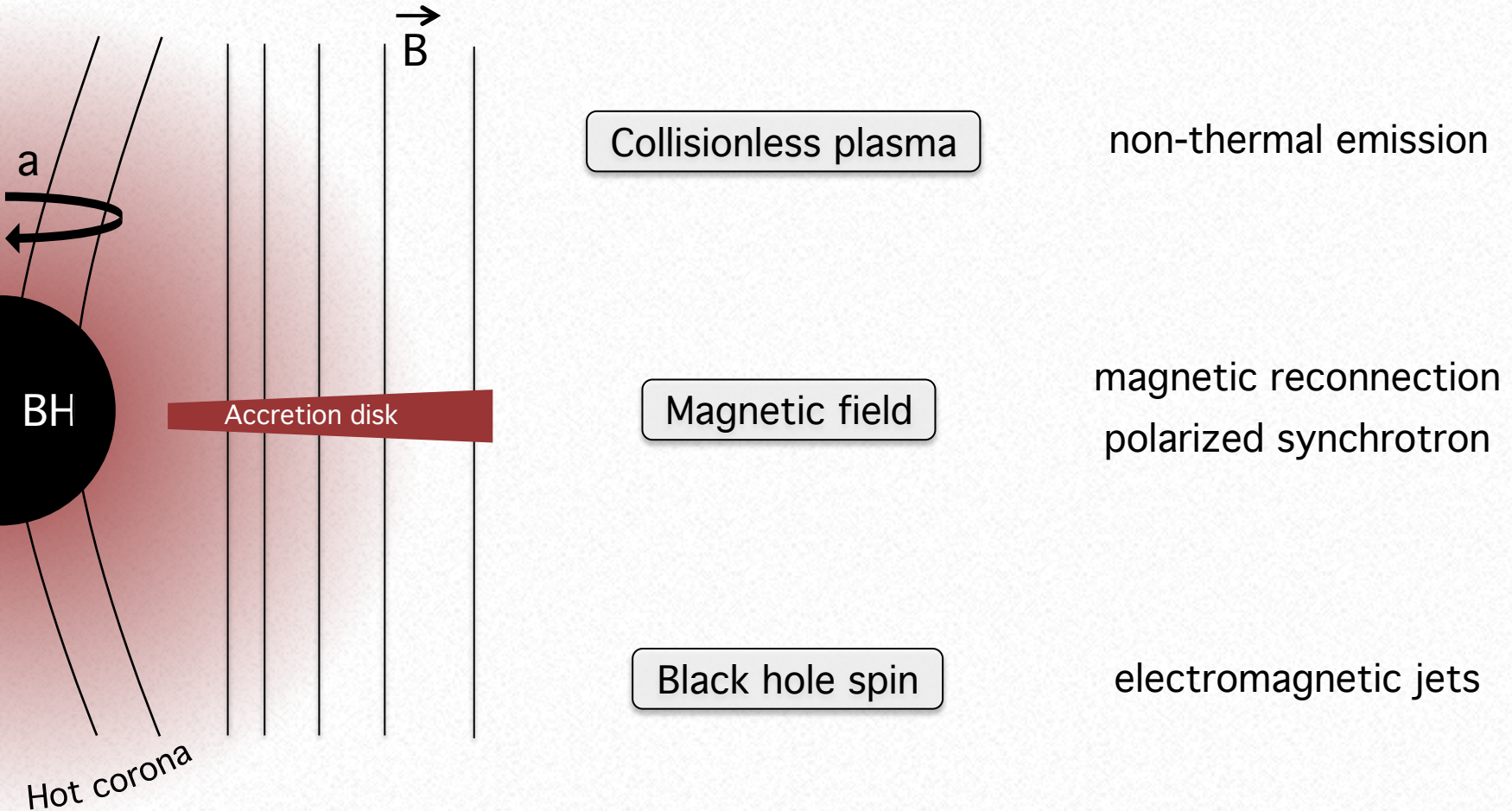


Dublin

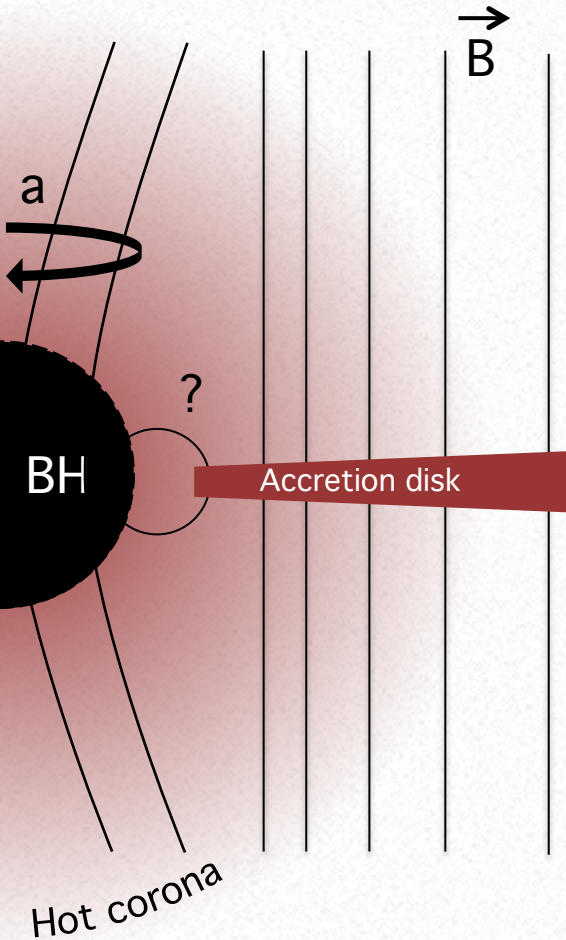
February 2023



Black hole magnetosphere - Ingredients



Black hole magnetosphere - Questions



Where and how are particles accelerated?

Where are the emission sites and how do they move?

What is the dependence on the BH spin?

Black hole magnetosphere - Sgr A*

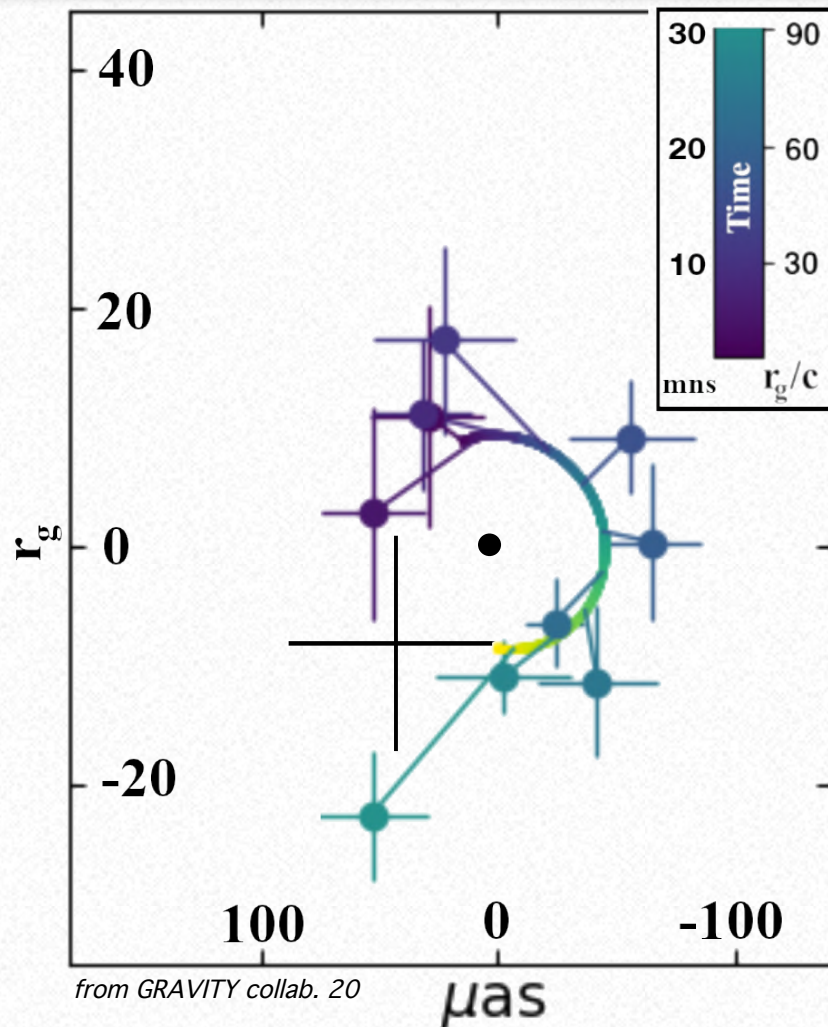
NIR non-thermal 1 h-long daily flares

Moving hot spot during flare => orb. period sep.

No modulated Doppler boosting => face-on

Shift between orbital & S2 center

Steady out-of-plane motion?



Outline

Axisymmetric
magnetosphere

Numerical setup
The physical mechanism
Dissipation
Synchrotron spectra & images



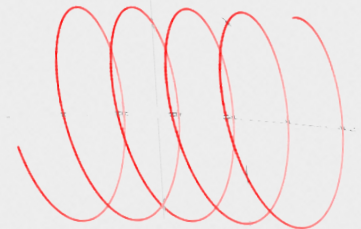
Full 3D
magnetosphere

Motivations
Hot spots
Constrains on Sgr A* spin

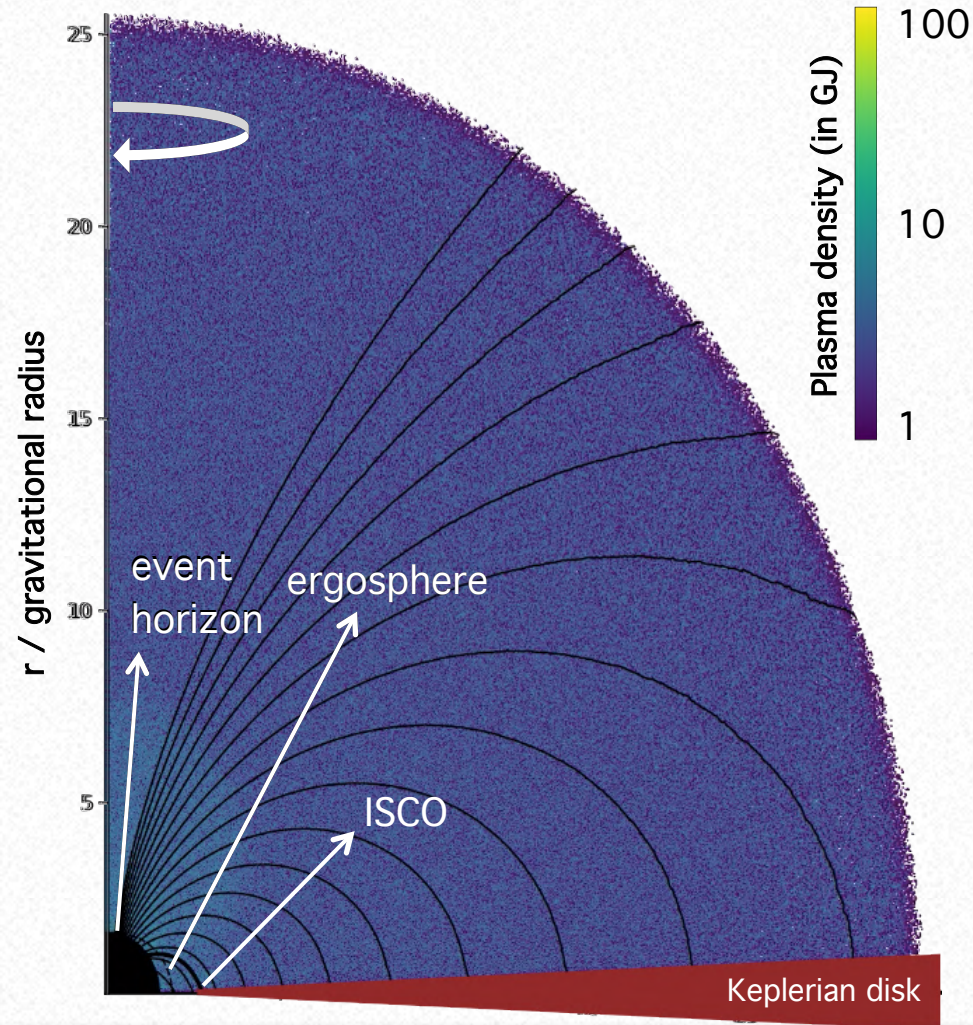


Synthetic
observables

Model
Light curve & astrometry
The timing crisis



Numerical setup



Kerr spacetime in KS coordinates

Axisymmetric grid

- ↳ from $0.9r_H$ to $\sim 30r_g$ (stretched)
- ↳ from 0 to $\pi/2$ (uniform)
- ↳ 2048 x 1120, $\#10^8$ particles

=> skin depth & Larmor radius resolved

Pair plasma injection

- ↳ ad hoc such as force-free

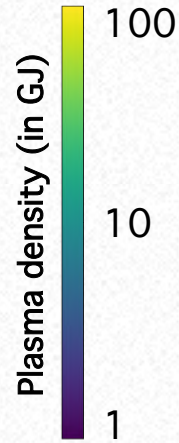
Boundary conditions

Uzdensky 04, 05
Yuan+19 a,b

The physical mechanism

time =

$a=0.8$

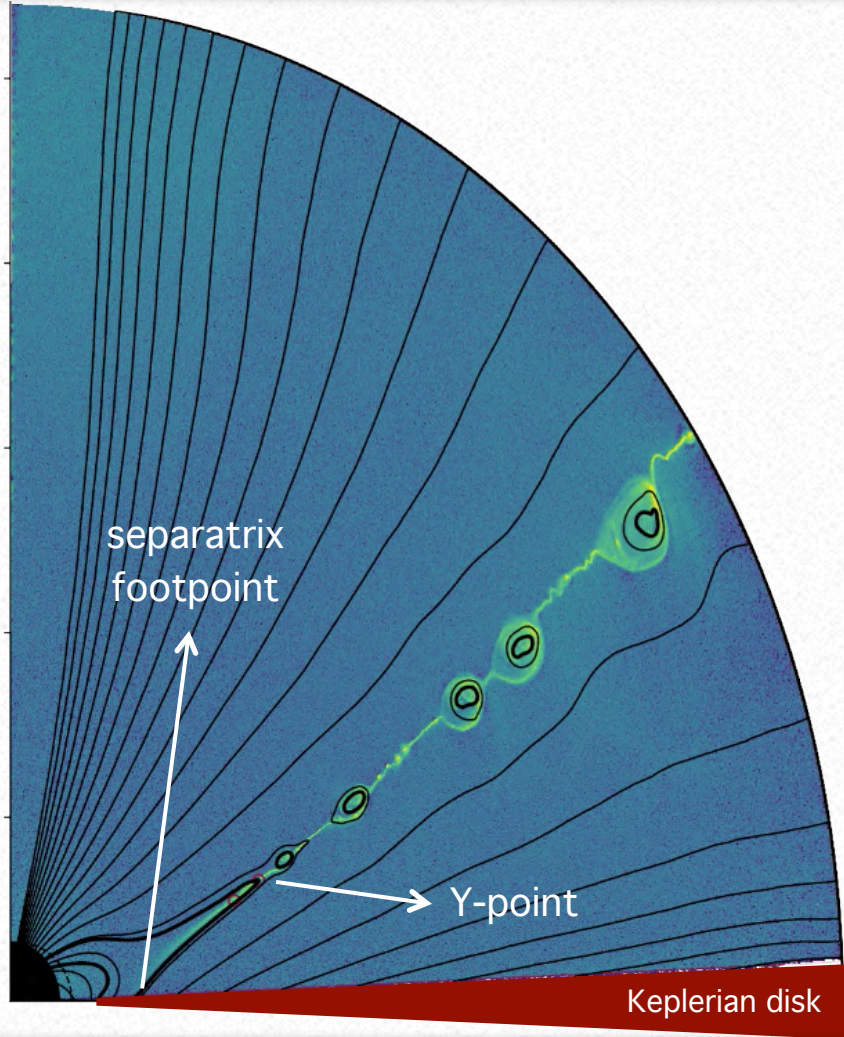


- Open field lines anchored in BH => BZ
- Open field lines anchored in disk => BP
- Disk-BH coupling field lines
- Current sheet from Y-point

IEM, Cerutti, Cironquand & Paffrey 22

Keplerian disk

Hybrid magnetic topology - 4 zones

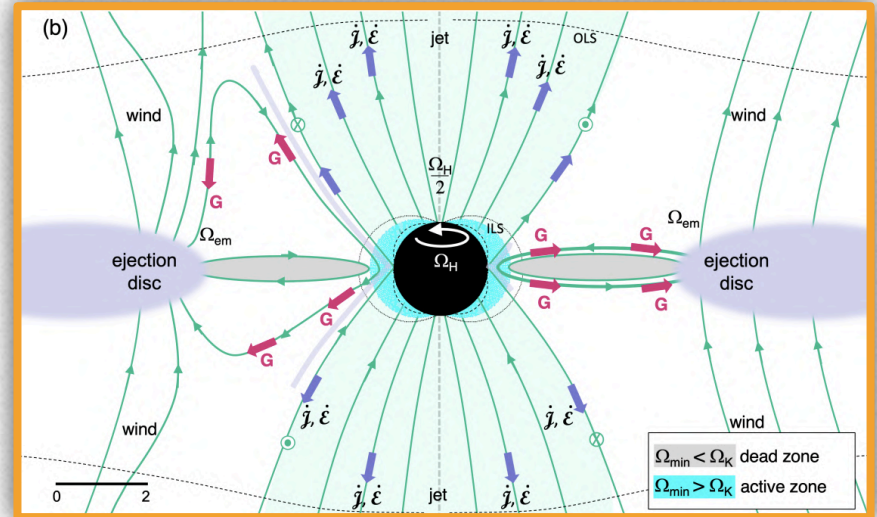


Open field lines anchored in BH => BZ

Open field lines anchored in disk => BP

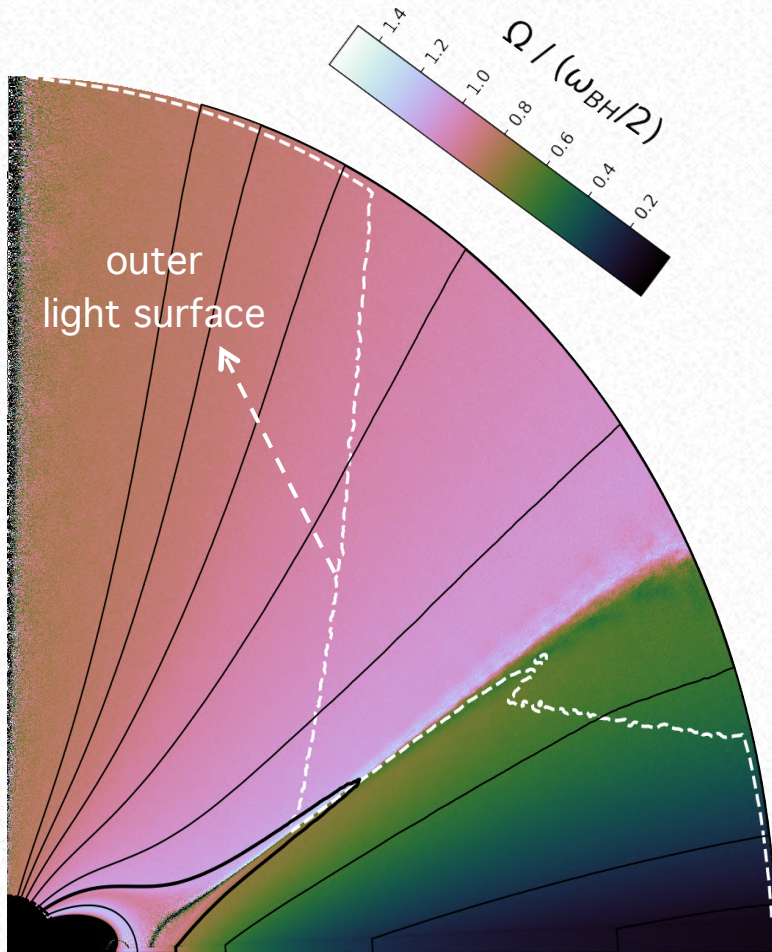
Disk-BH coupling field lines

Current sheet from Y-point



Blandford & Globus 22

An essentially force-free magnetosphere - Angular speed of B field lines

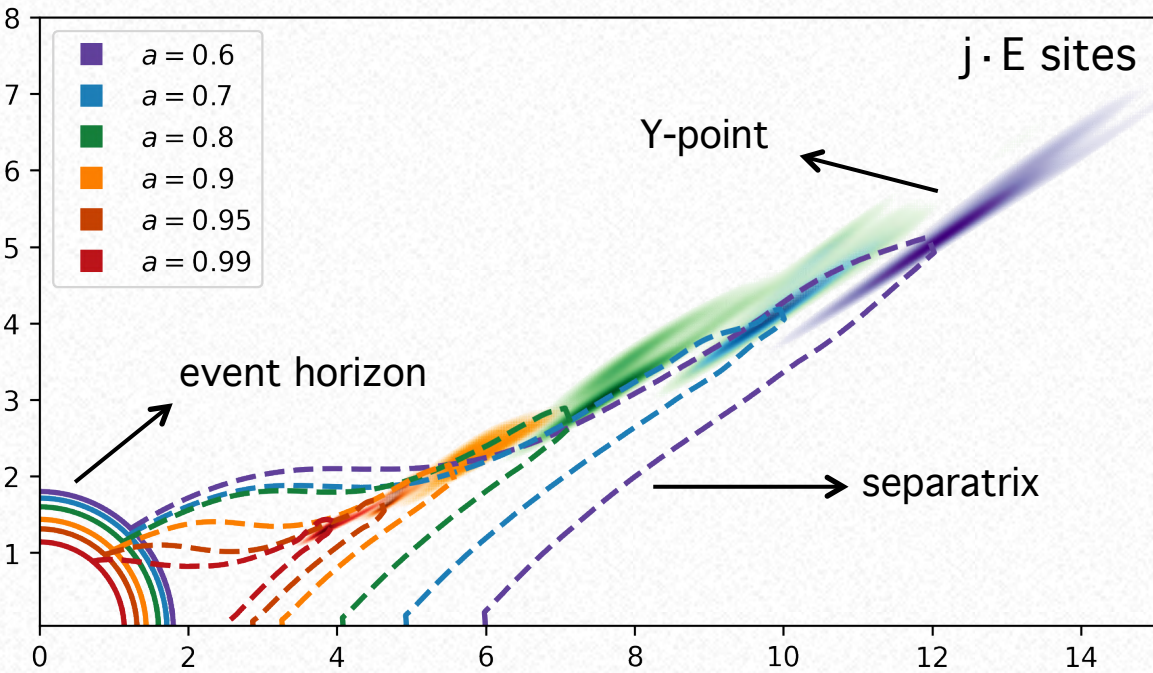


Optimal angular speed in jet

Outer light surface \cap current sheet \Rightarrow Y-point

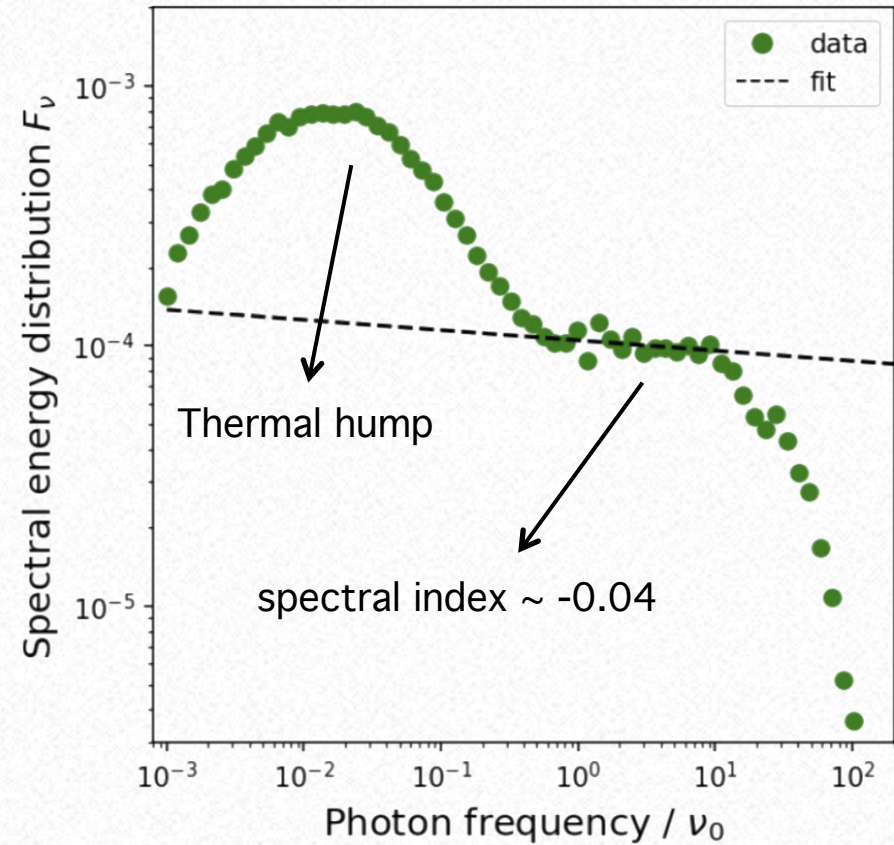
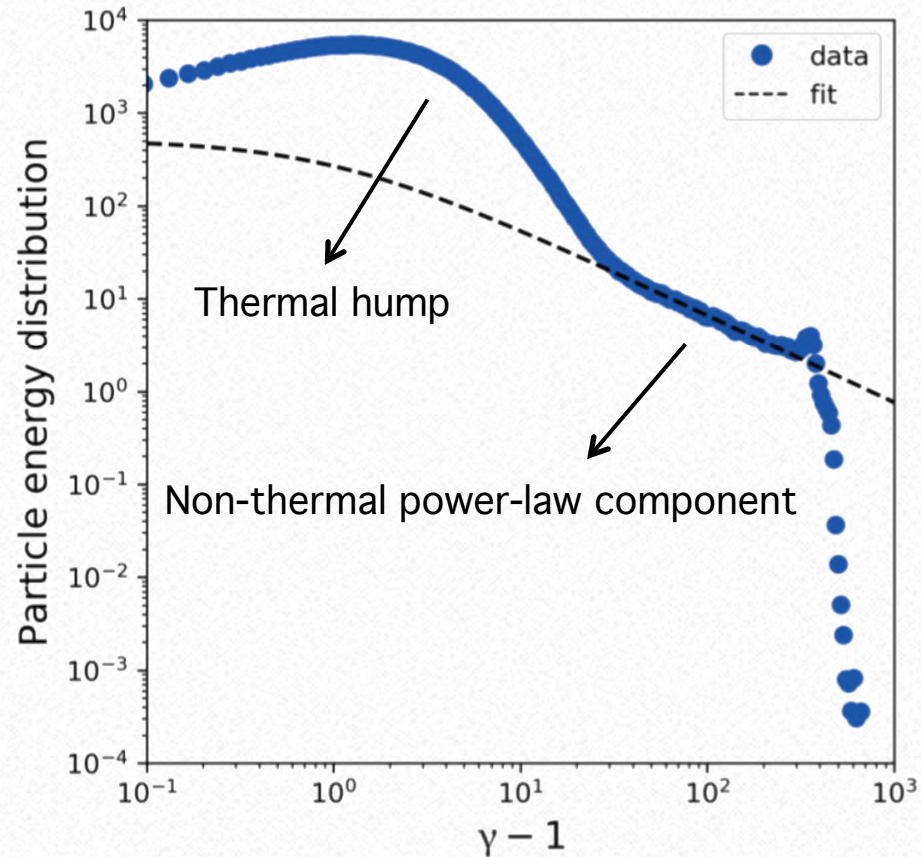
Angular speed jump at current sheet

Significant dissipation of EM energy @ Y-point



Synthetic observables - Synchrotron spectra

High energy power-law component produced by e^+/e^- accelerated @ B reconnection sites



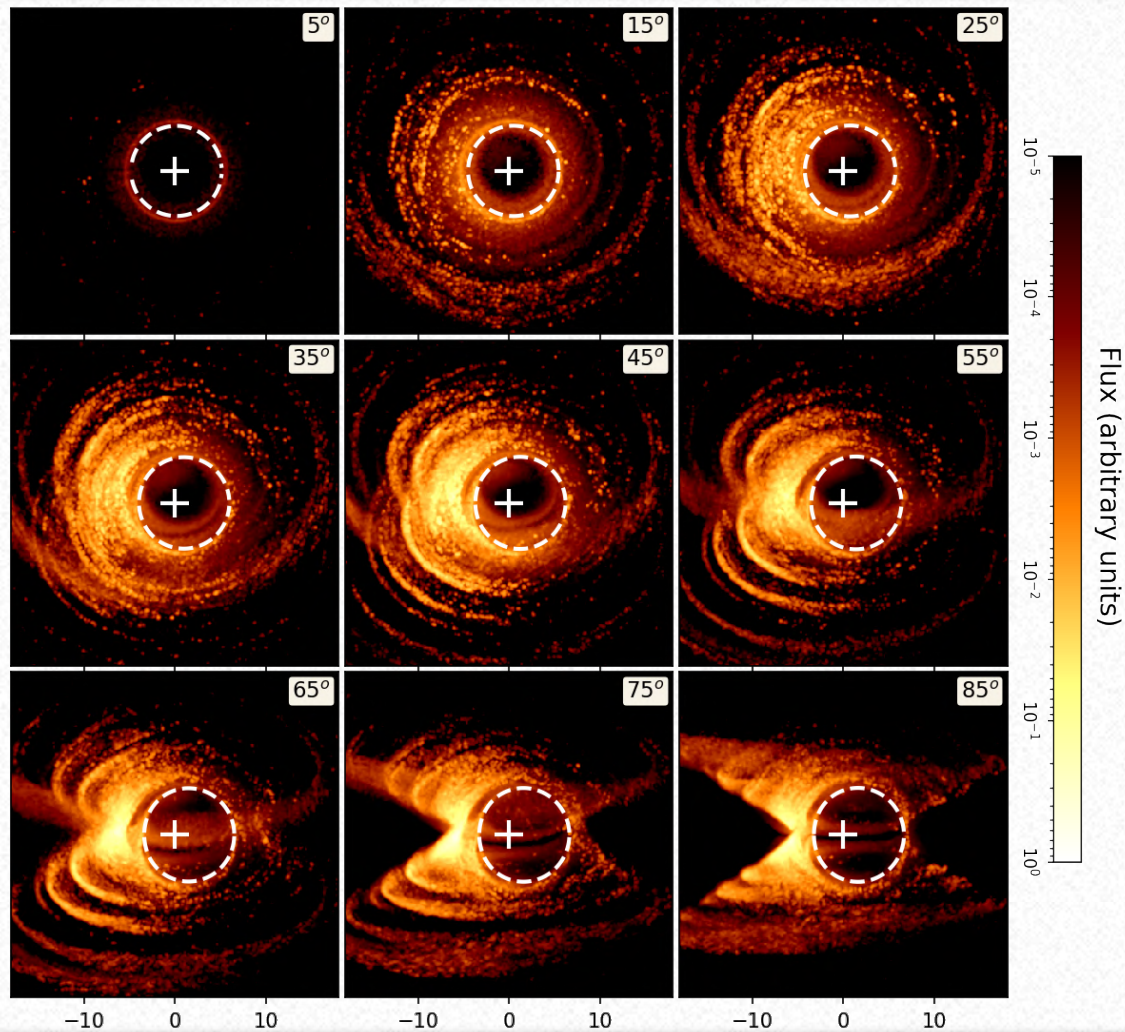
Synthetic observables - Synchrotron images

geokerr

BH spin = 0.8

Shadow

Y-reconnection rings



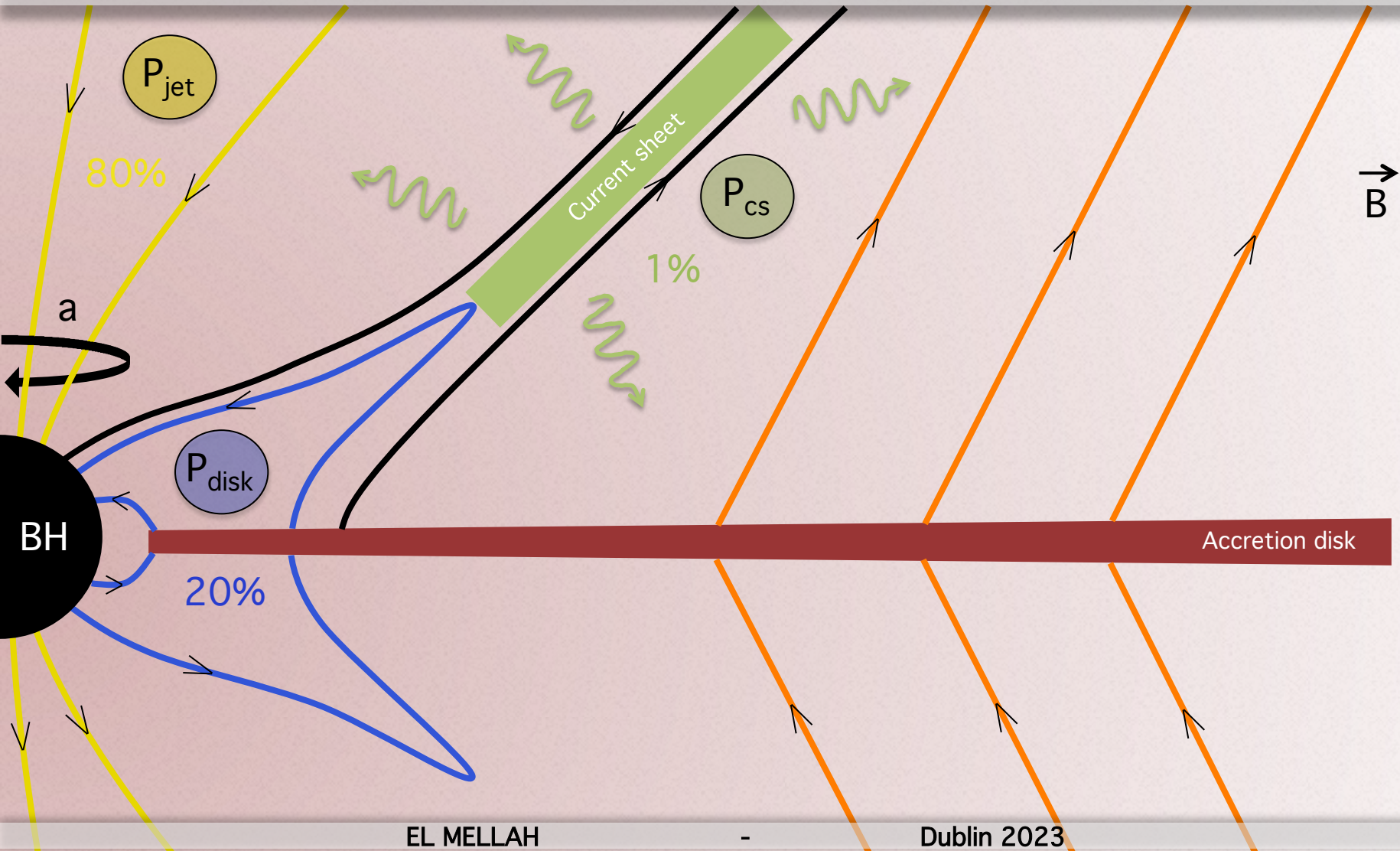
Crinquad+22

EL MELLAH

Dublin 2023

06/17

Intermezzo - 2.5D summary



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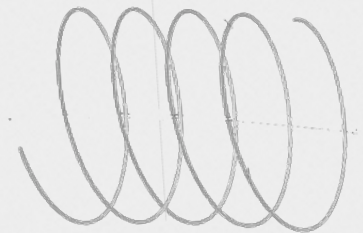
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Hot spots
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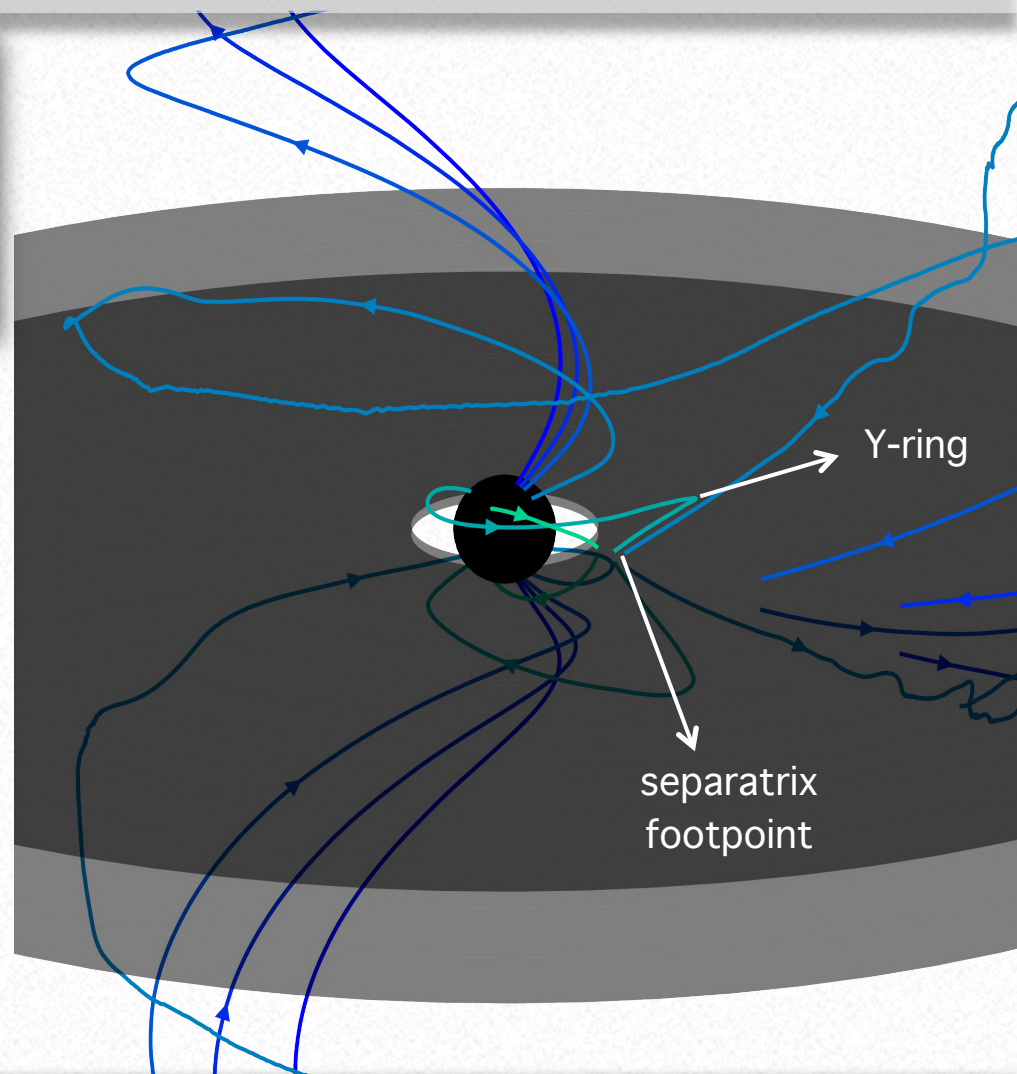
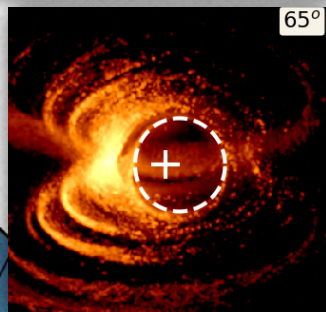
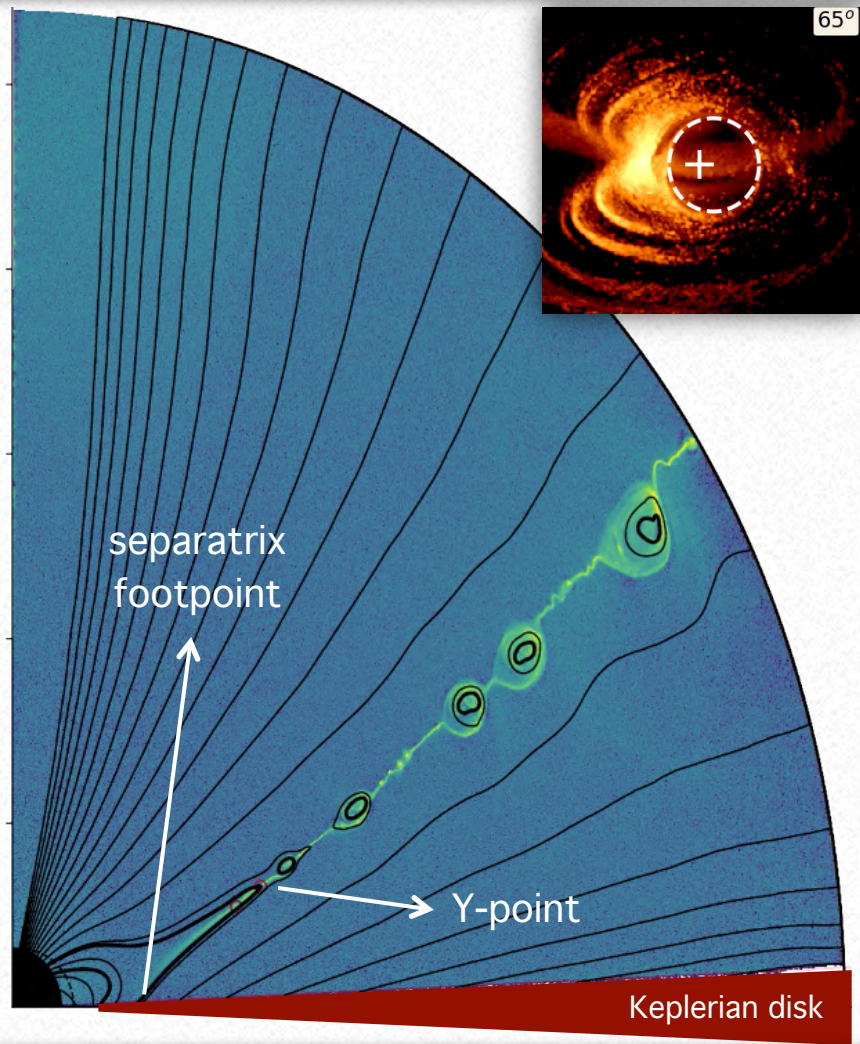


Synthetic
observables

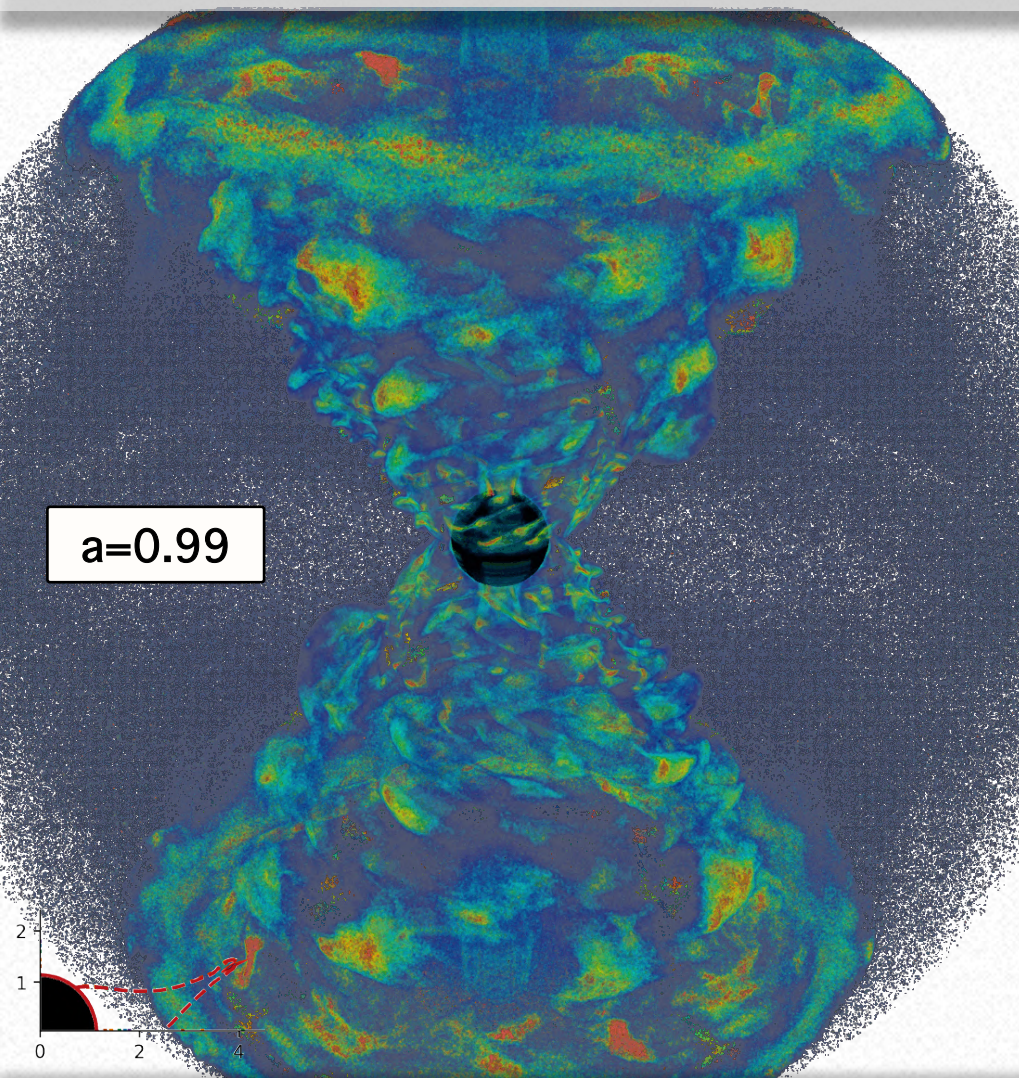
Model
Light curve & astrometry
The timing crisis



Motivation



Current sheet - Volume rendering



IEM, Cerutti & Crinquand (in prep.)

Resolution

- ↳ 512 x 256 x 256
- ↳ ~ 20 particles per cell

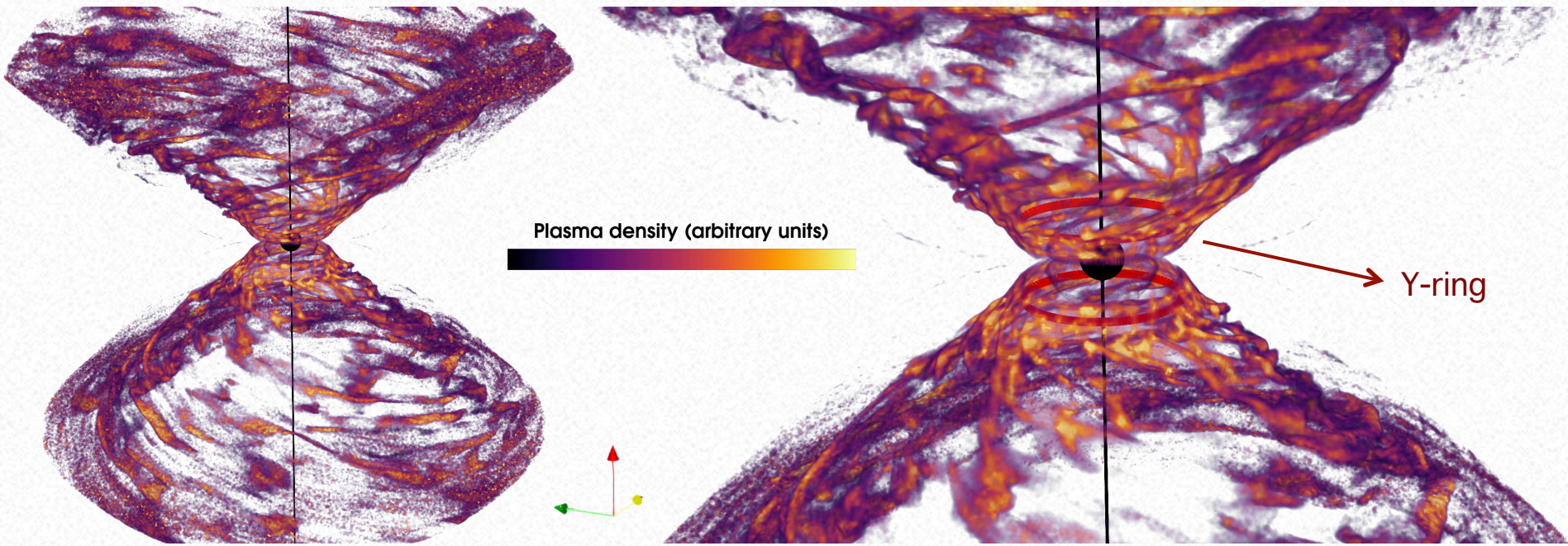
Relaxation from axisymmetric setup

Very similar to 2.5D

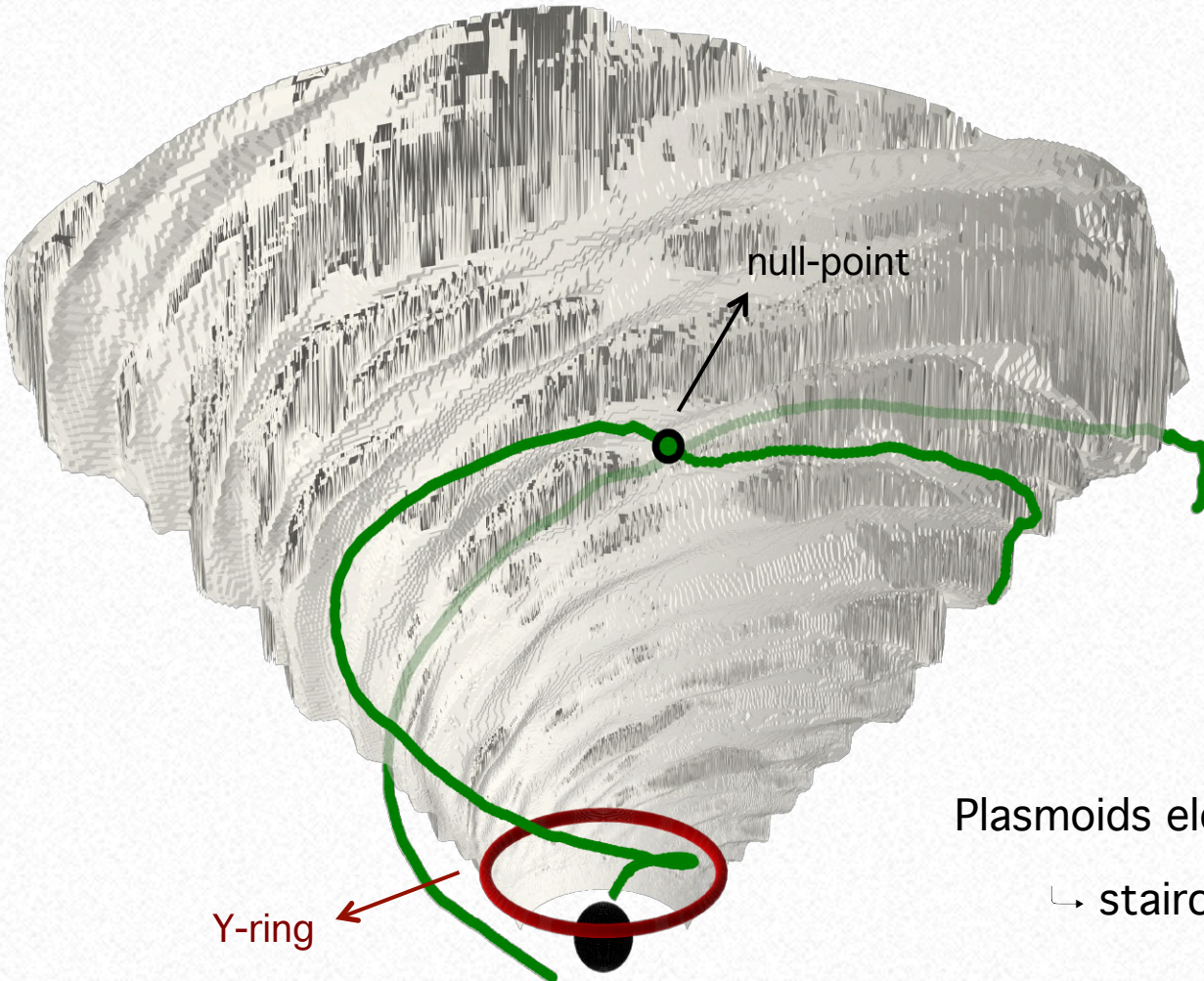
BUT

- ↳ tearing inst. along ϕ -direction
- ↳ kink instabilities

Current sheet - Volume rendering



Current sheet - Surface



J. van der Straet 1587



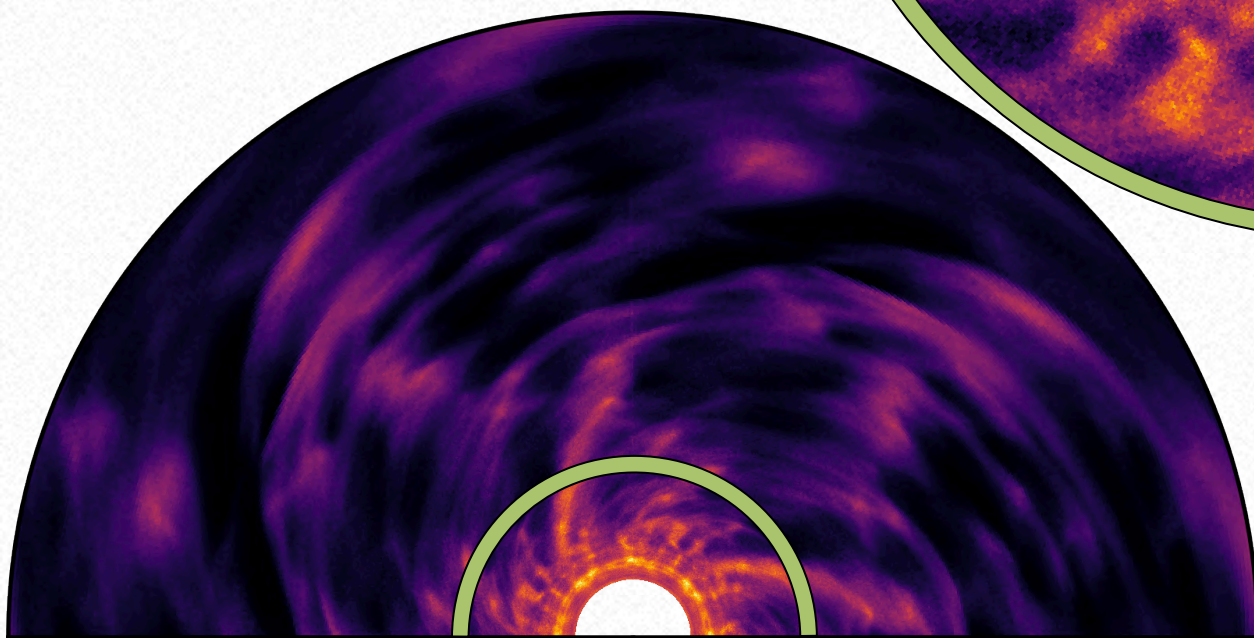
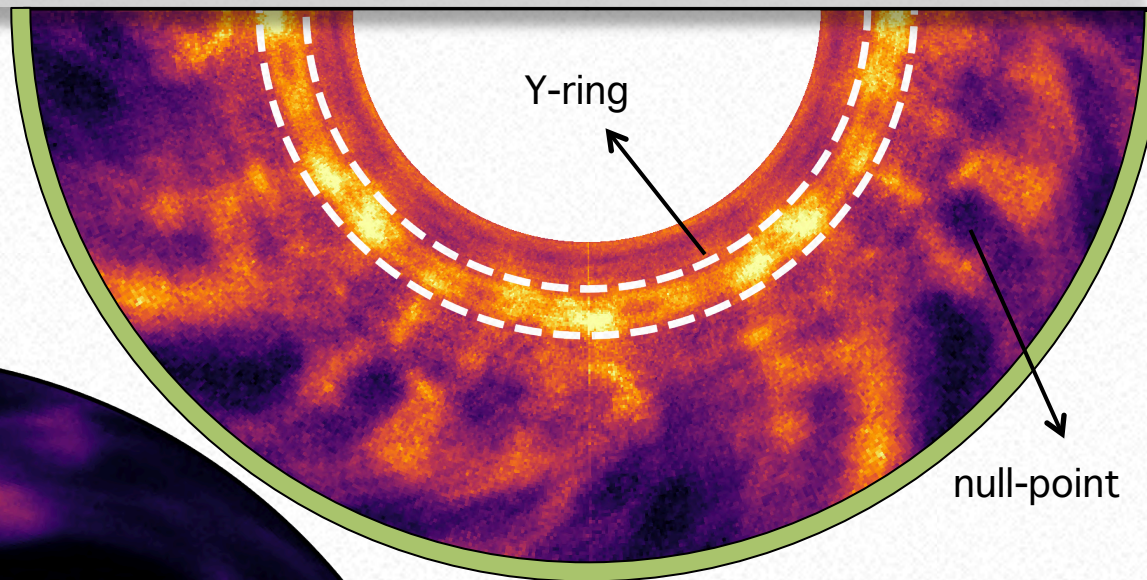
Plasmoids elongated in ϕ -direction
↳ staircase pattern along jet sheath

Current sheet - Projection

Tracing flux ropes

- ↳ outflowing from Y-ring
- ↳ merge into macroscopic

Cerutti & Giacinti 22



Relativistic reconnection rate

- ↳ $\beta_{\text{rec}} \gtrsim 7\%$

0 5 10 15 20 25

Flux ropes - Trajectory

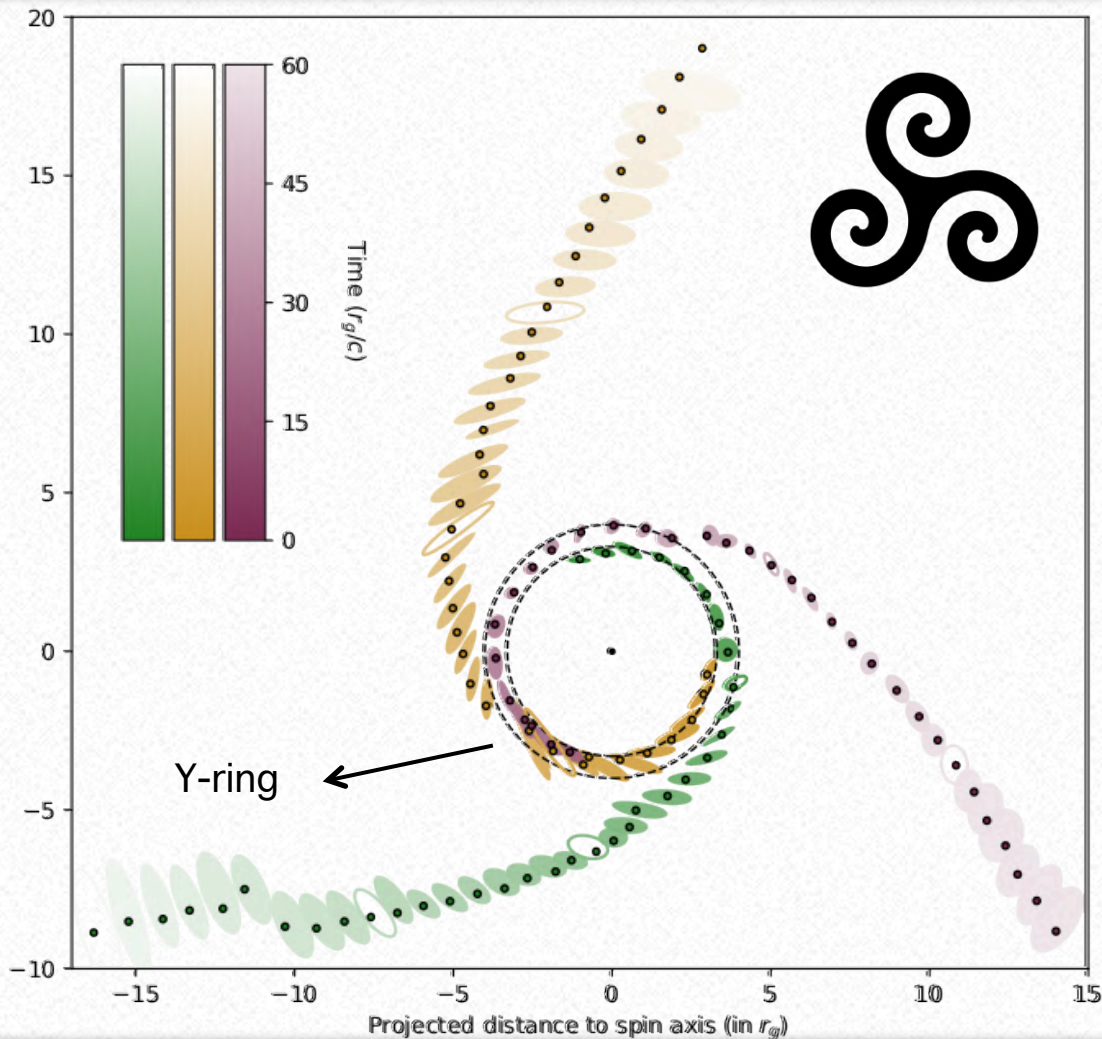
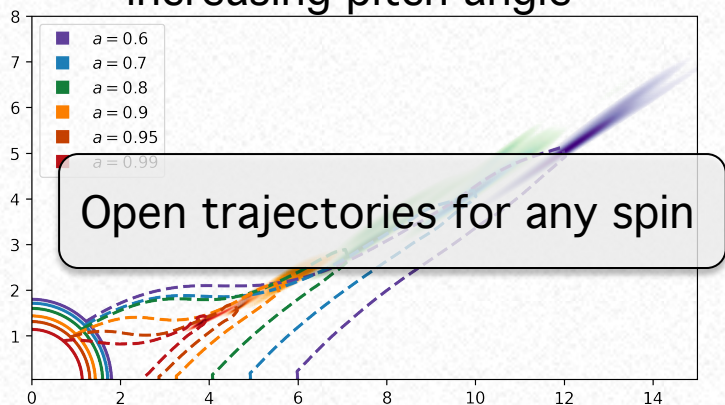
Face-on projection on plane of sky

Loading phase

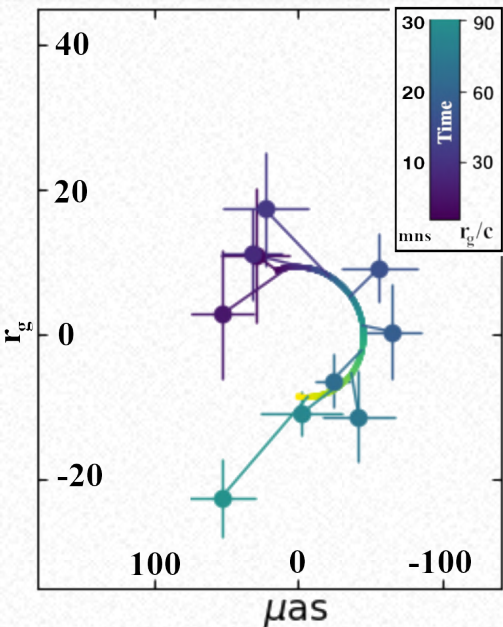
↳ super-Keplerian motion

Outflowing expansion phase

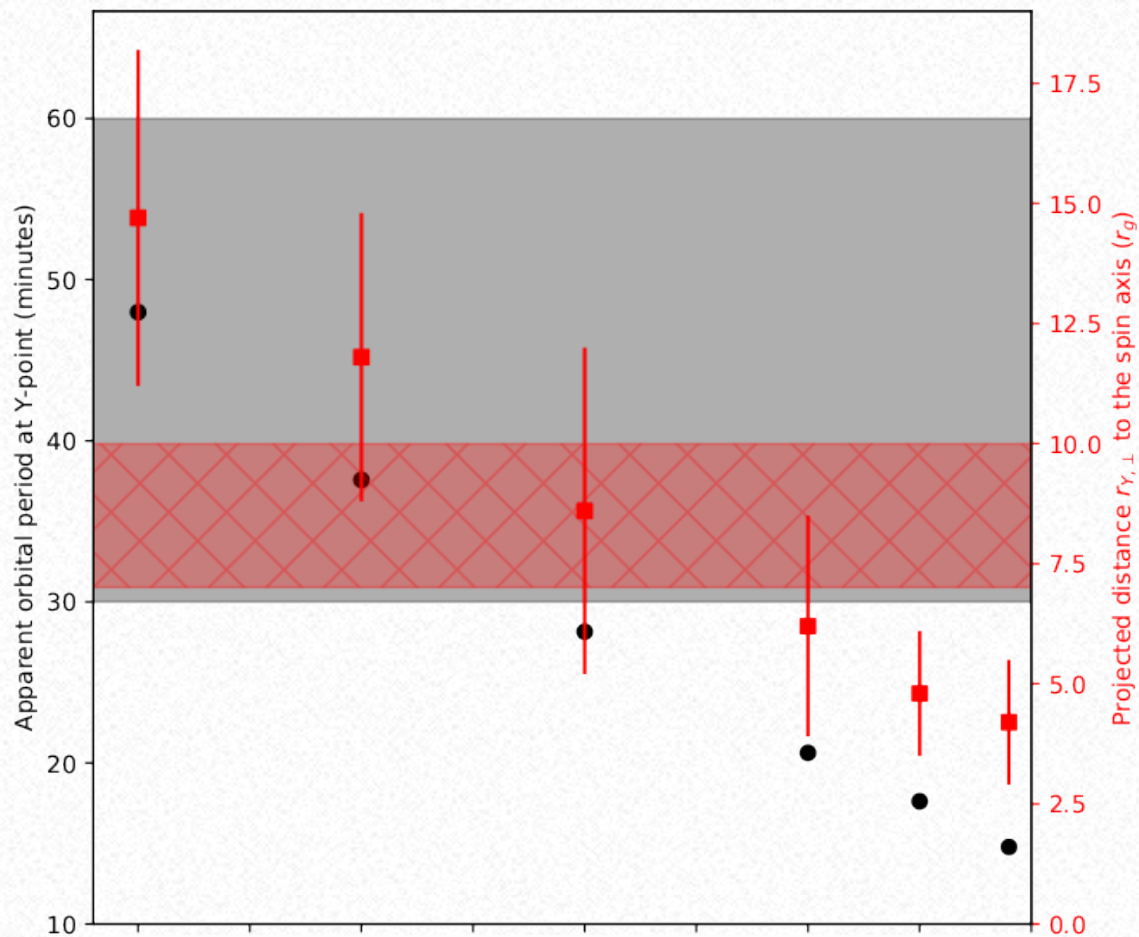
↳ increasing pitch angle



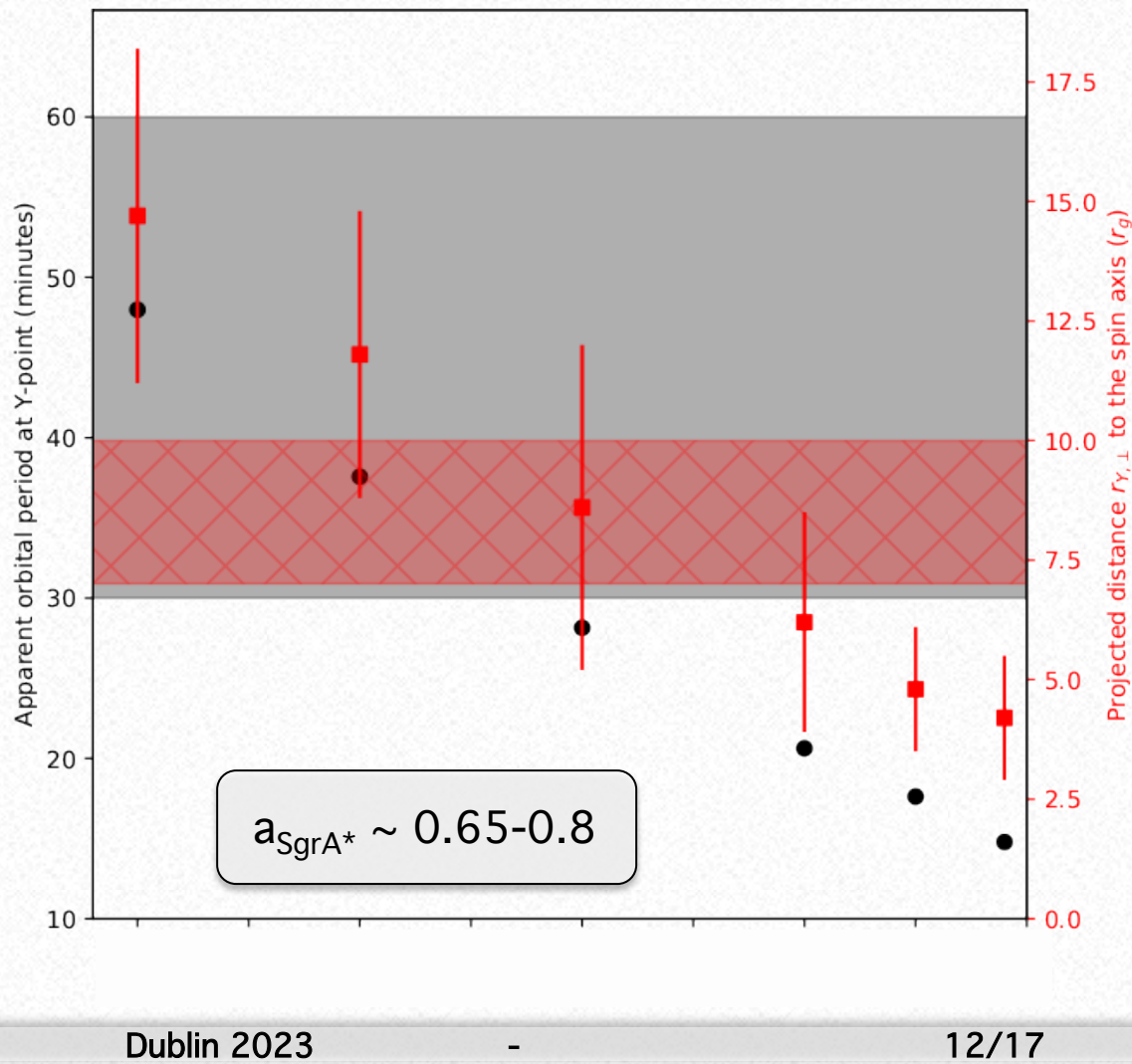
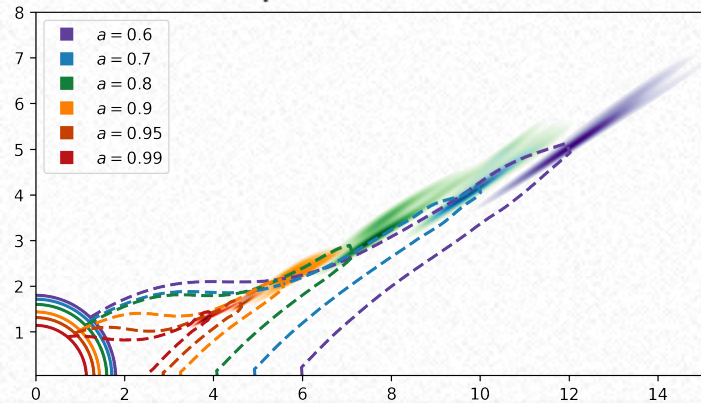
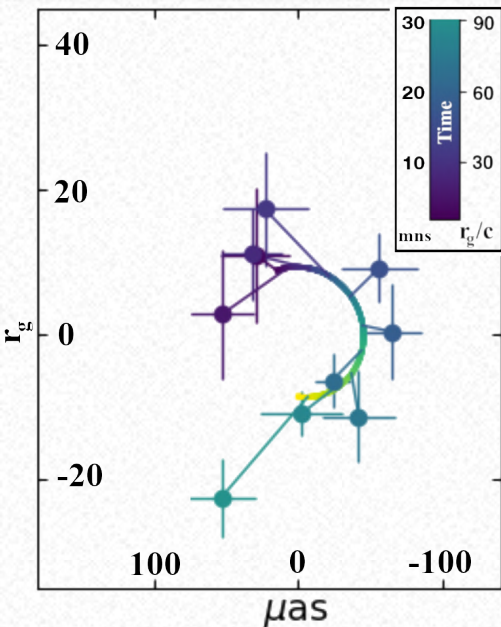
Constraints on Sgr A* spin



- ↳ motion timing
- ↳ distance to spin axis



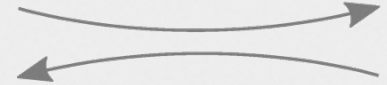
Constraints on Sgr A* spin



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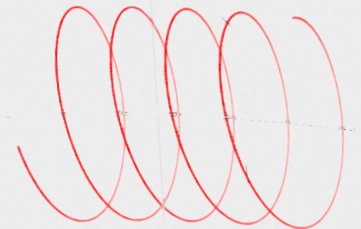
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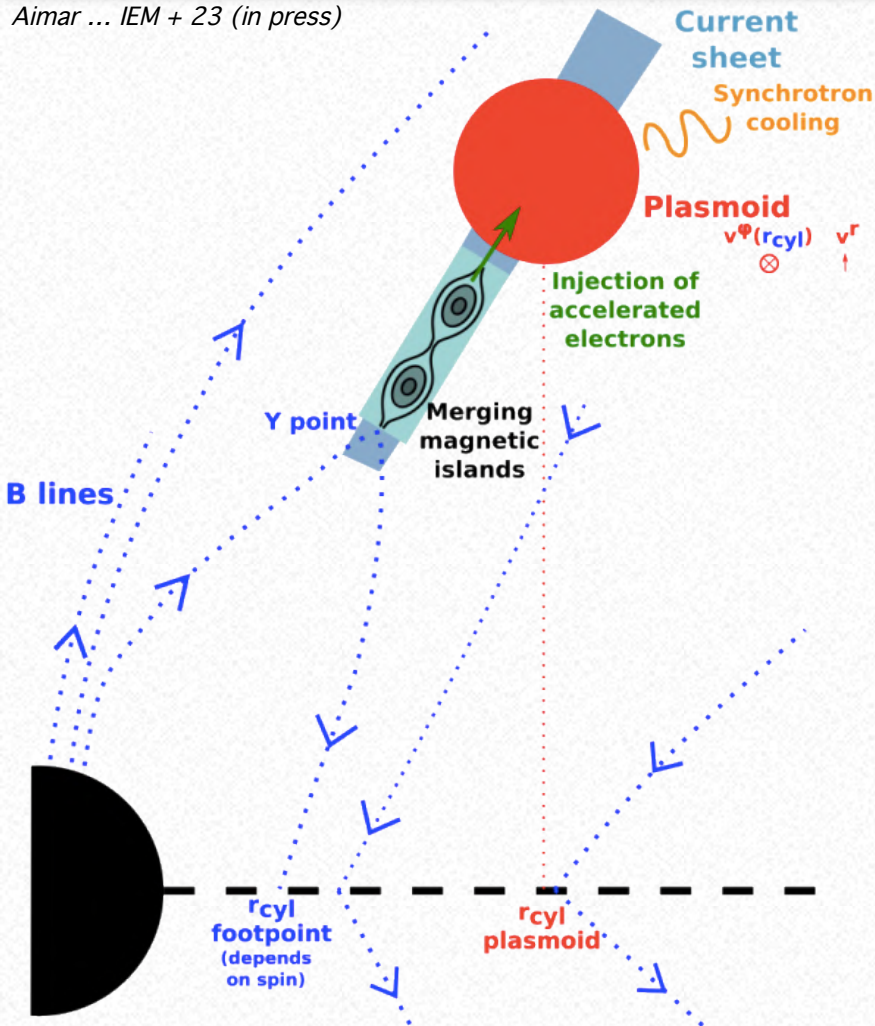
Synthetic
observables

Model
Light curve & astrometry
The timing crisis



Synthetic observables - Model

Aimar ... IEM + 23 (in press)



Plasmoid kinematics

↳ from GR-PIC

IEM + 22

Electron distribution function

↳ EMBLEM code

Dmytriev + 21

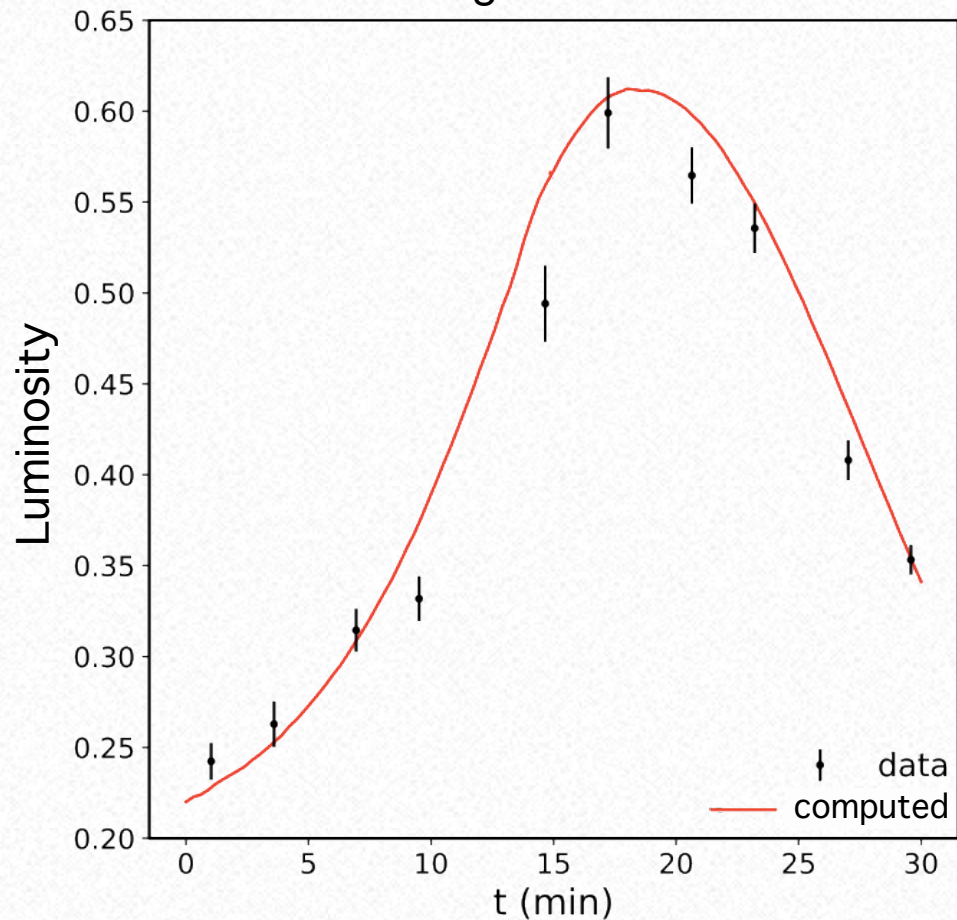
Ray-tracing

↳ GYOTO code

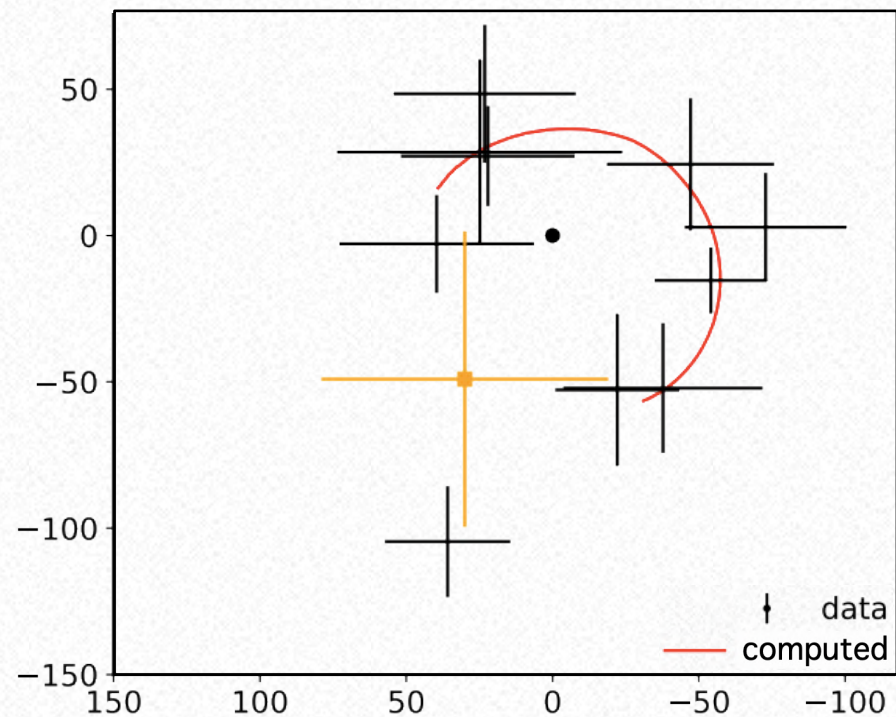
Paumard + 19

Synthetic observables - Light curve & astrometry

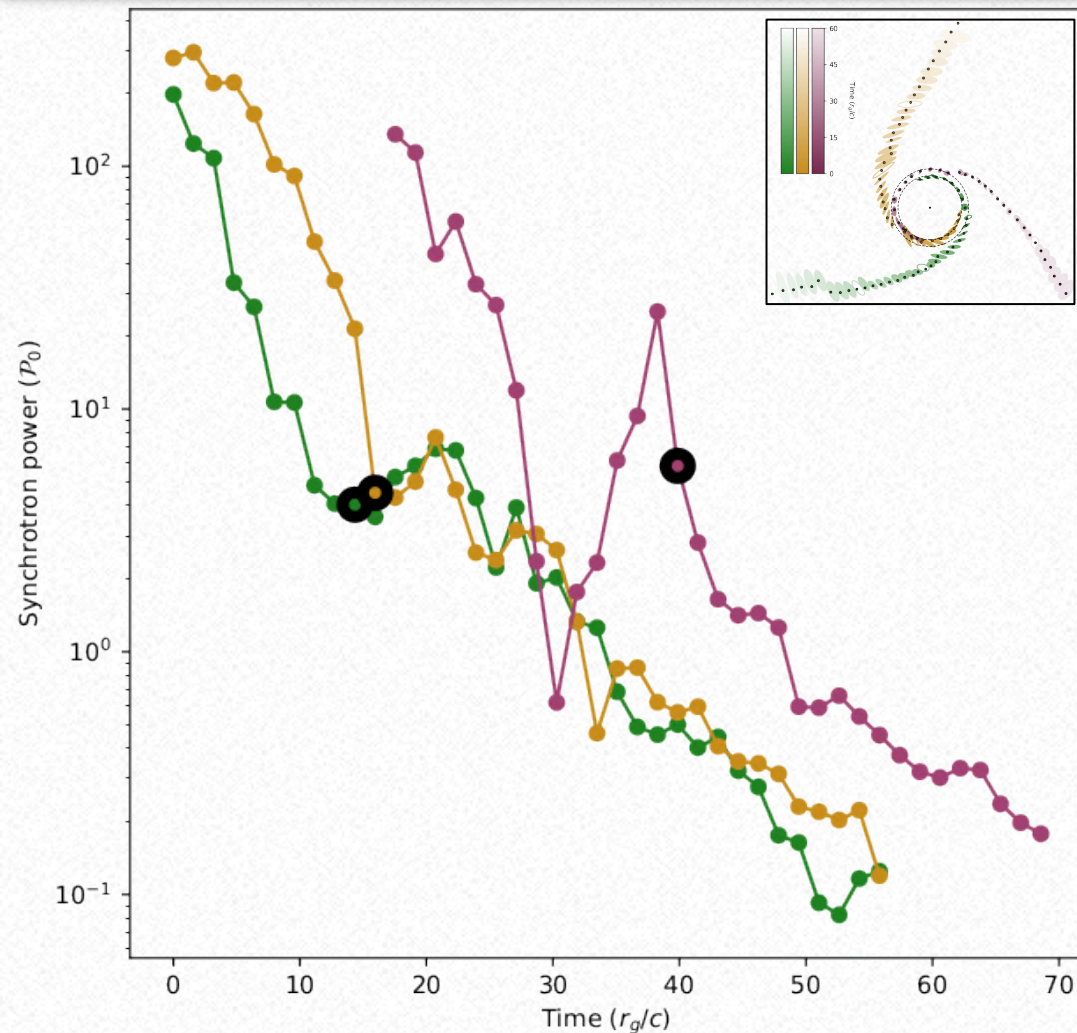
Light curve



Astrometry



Synthetic observables - The timing crisis



$\gamma \sim 100 - 1,000$

Peak emission coherent

↳ NIR

↳ $10^{35} \text{ erg} \cdot \text{s}^{-1}$

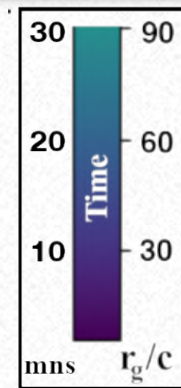
BUT

Major limitation for any spin

↳ quick drop in a few $10 r_g/c$

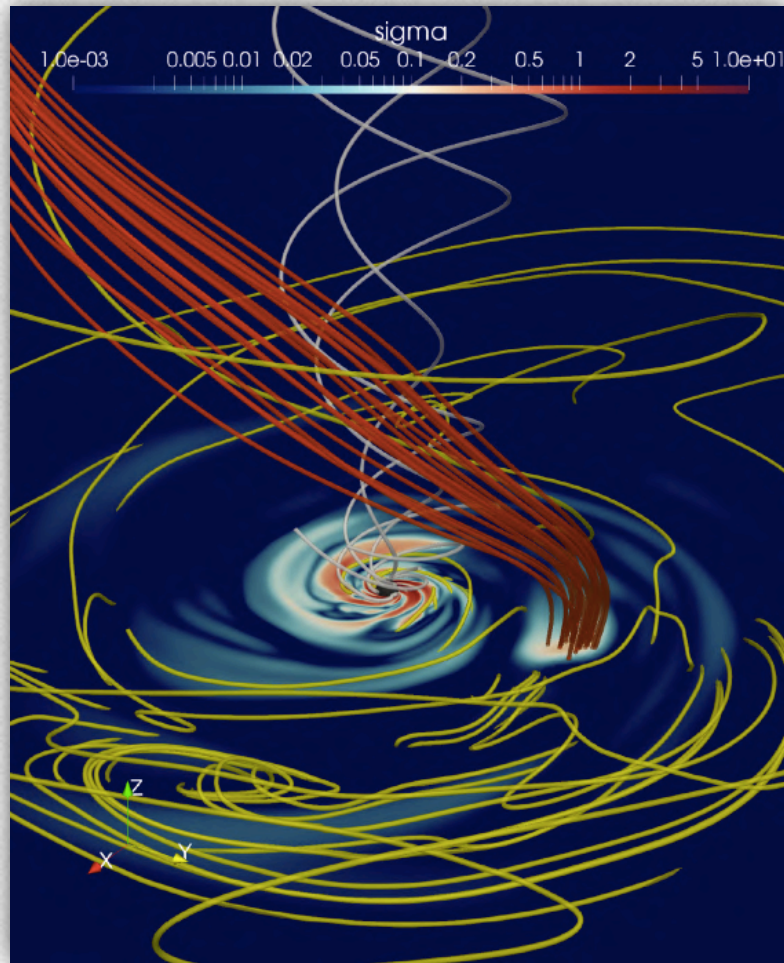
↳ due to B drop

A single plasmoid can't make it

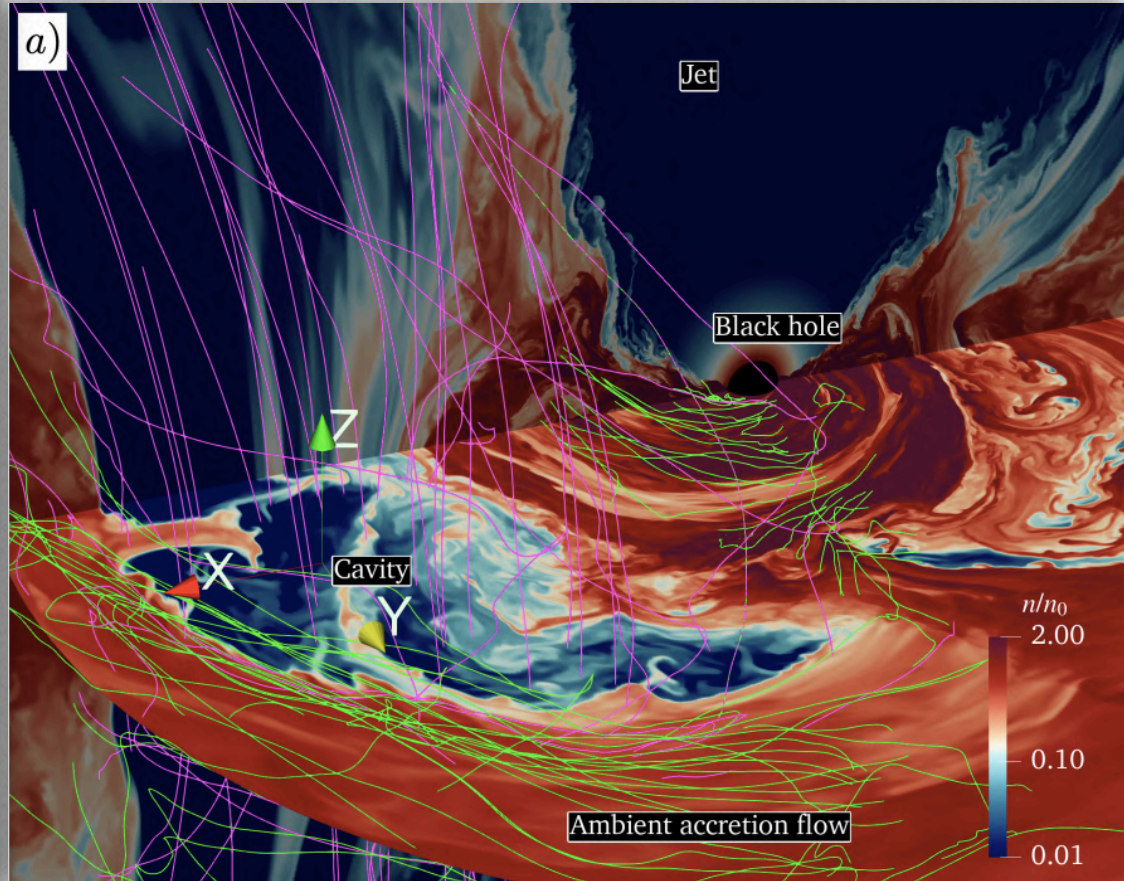


Underlying magnetic field topology in the disk

Zhdankin+23

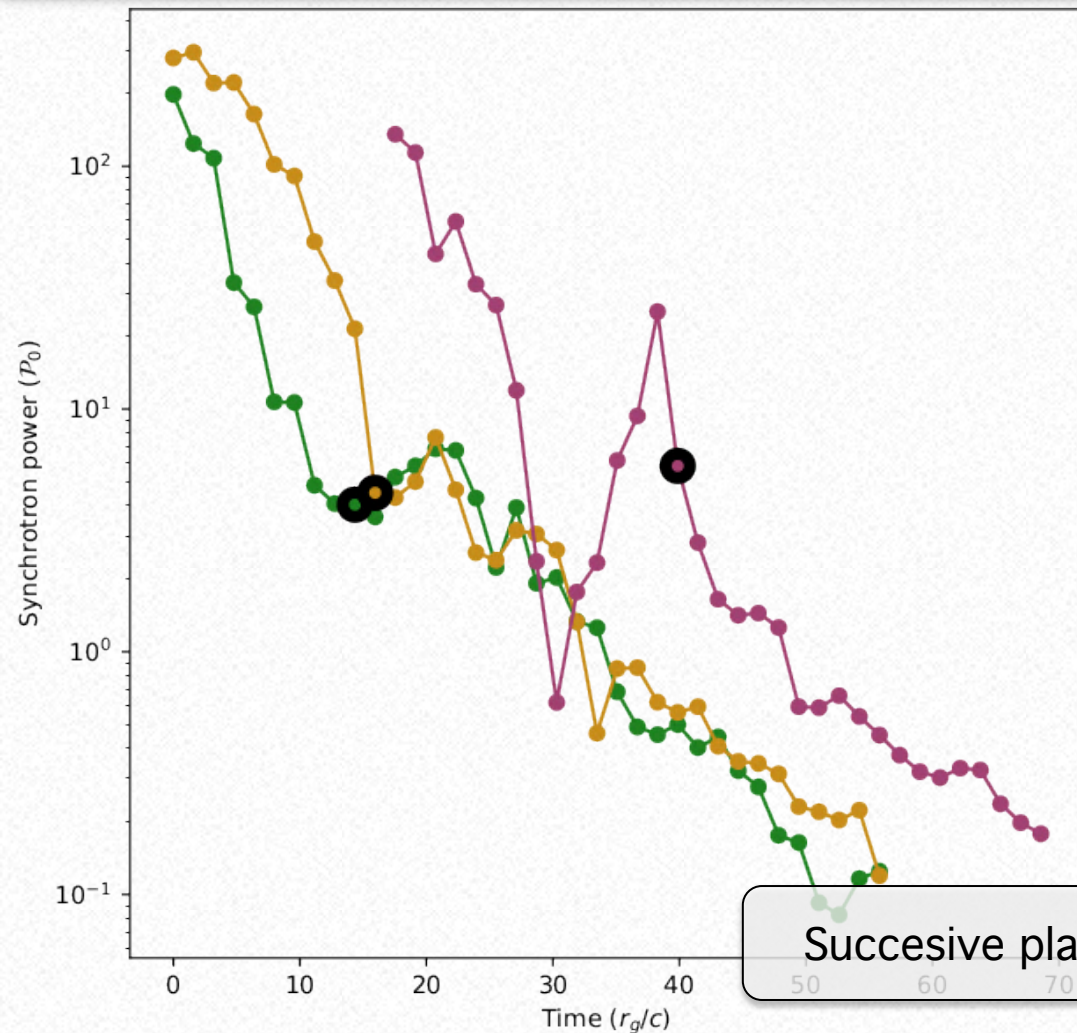


Porth+21

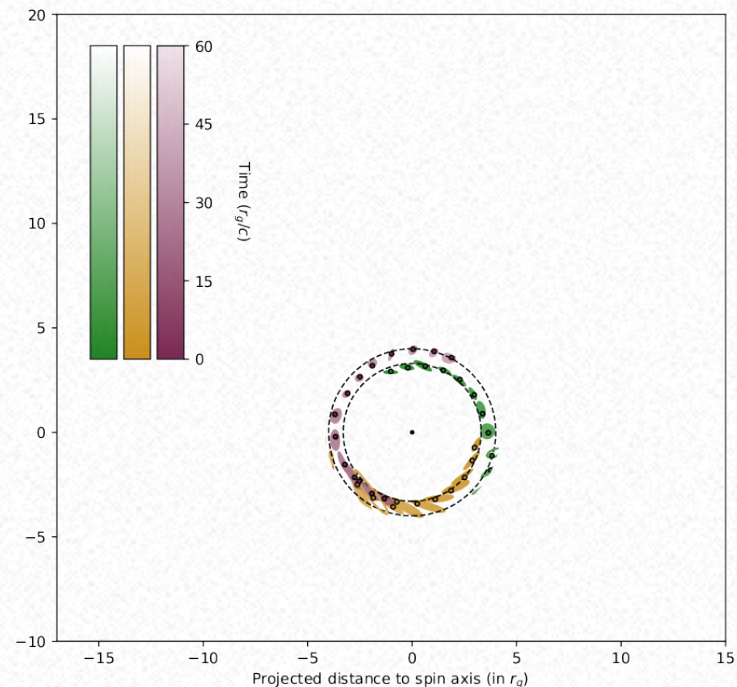


=> finite azimuthal extent of magnetic structures

A shimmering pearl necklace



Onset of plasmoids @ rotating Y-arc



Successive plasmoids from finite azimuthal sector

Summary

Axisymmetric
magnetosphere

4 regions | BZ / BP
closed
current sheet
Y-point @ outer light surface
B reconnection => power-law



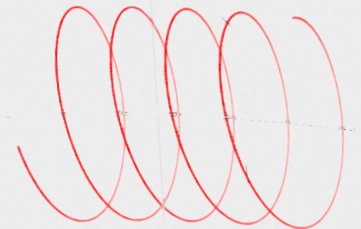
Full 3D
magnetosphere

Twisted flux ropes
Magnetic slingshot
 $a_{\text{SgrA}^*} \sim 0.65-0.8$



Synthetic
observables

PIC + $f_e(\gamma, t)$ + RT
Single plasmoid scenario
Plasmoids in finite azimuthal sector



Perspectives

Hot spot

Astrometry and light curves

Alternative scenarios

B loops accretion

Stripped jets

Transient current sheets

Synthetic images

For Sgr A* and M87

Polarimetry

PIC + GRMHD = <3

$$\tau_{\text{GRMHD}} \gg \tau_{\text{PIC}}$$

Finite azimuthal extent of B