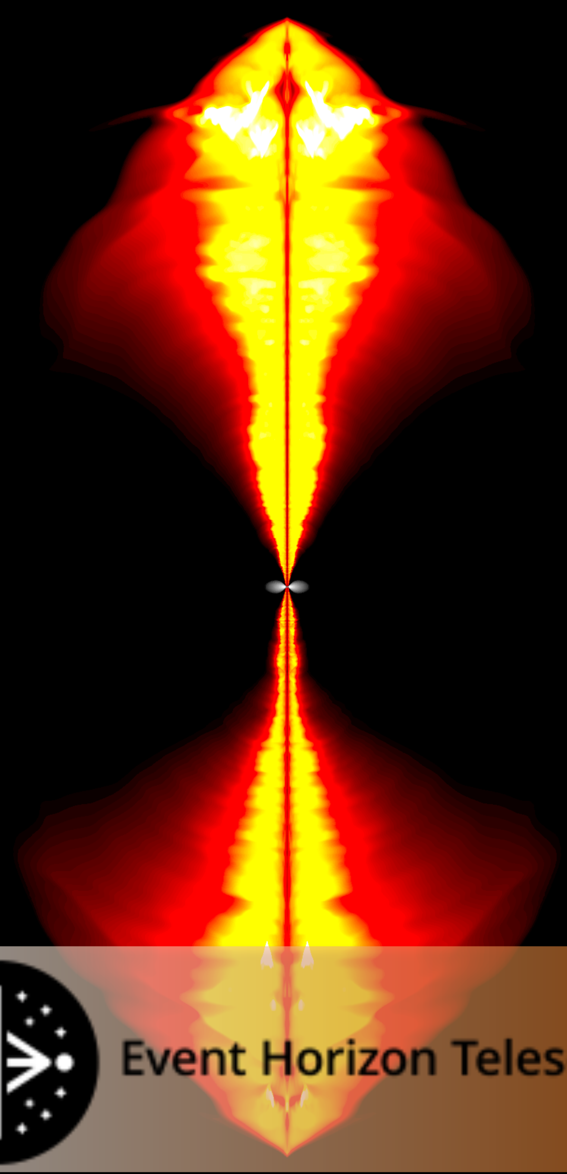
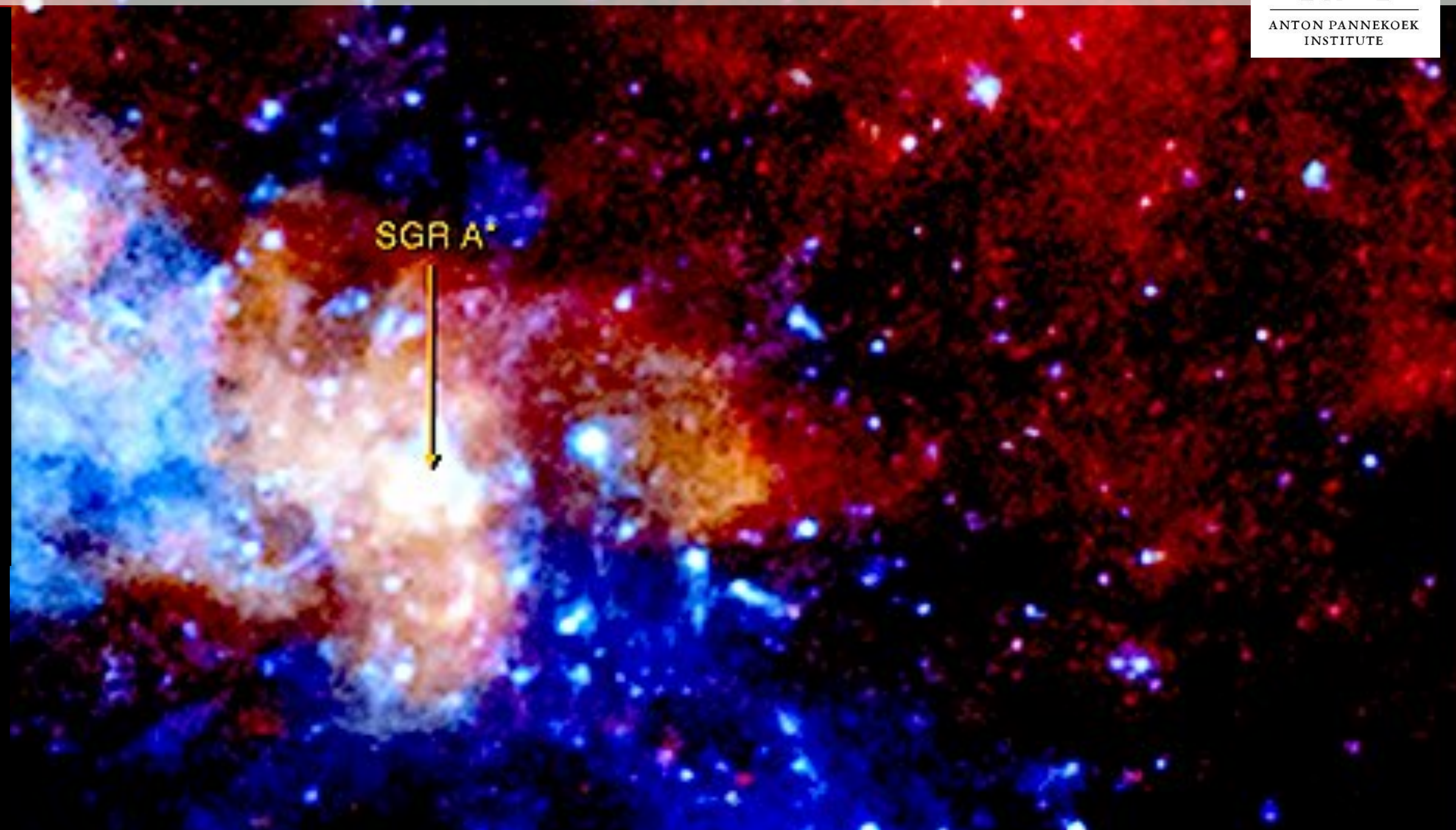
The first very high resolution GRMHD simulations of Sagittarius A*

Koushik Chatterjee[1]

20 years of Chandra
Boston, 2019





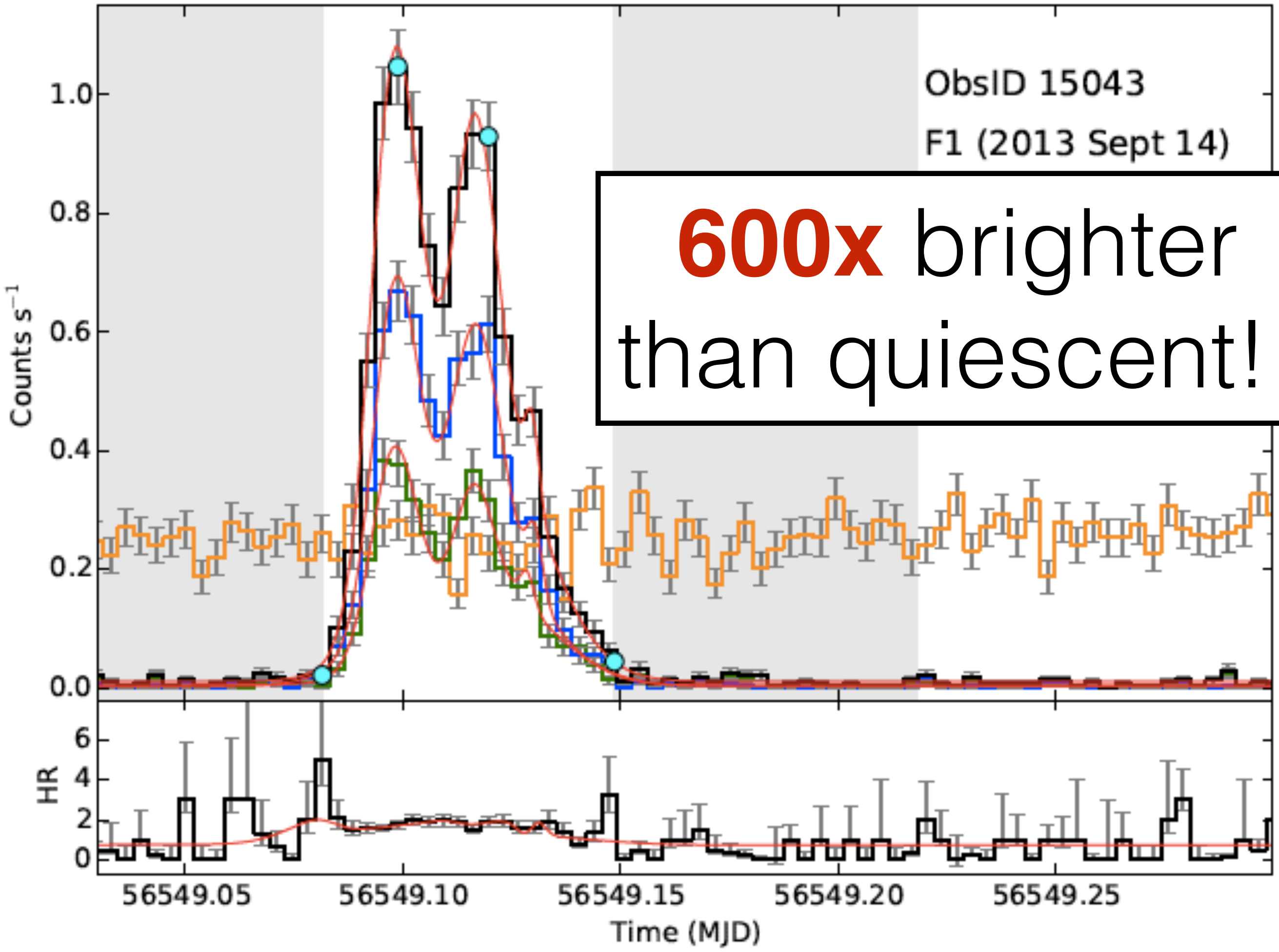
Matthew Liska[2], Doosoo Yoon[1], Sera Markoff[1], Alexander Tchekhovskoy[3], Ziri Younsi[4]

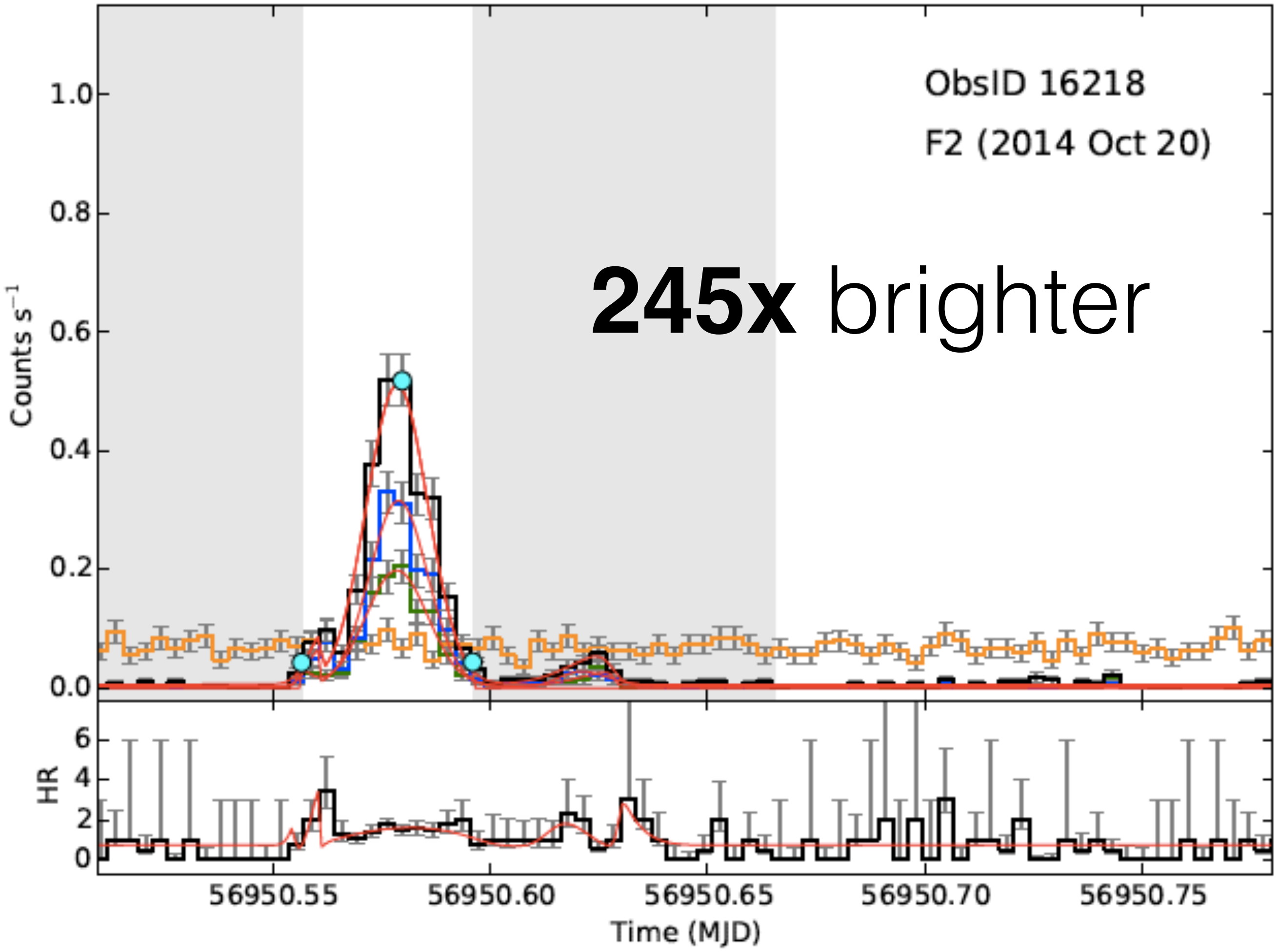
1: University of Amsterdam; 2: Harvard University; 3: Northwestern University; 4: University College London

NASA/CXC/MPE/G.Ponti et al 2015

Chandra captures brightest ever X-ray emission from Sgr A*: Flaring events

Haggard+2019





*But what is the physical mechanism behind **flaring**?*

*and why do we **care**?*

Markoff+2001

Microphysics of particle acceleration!!

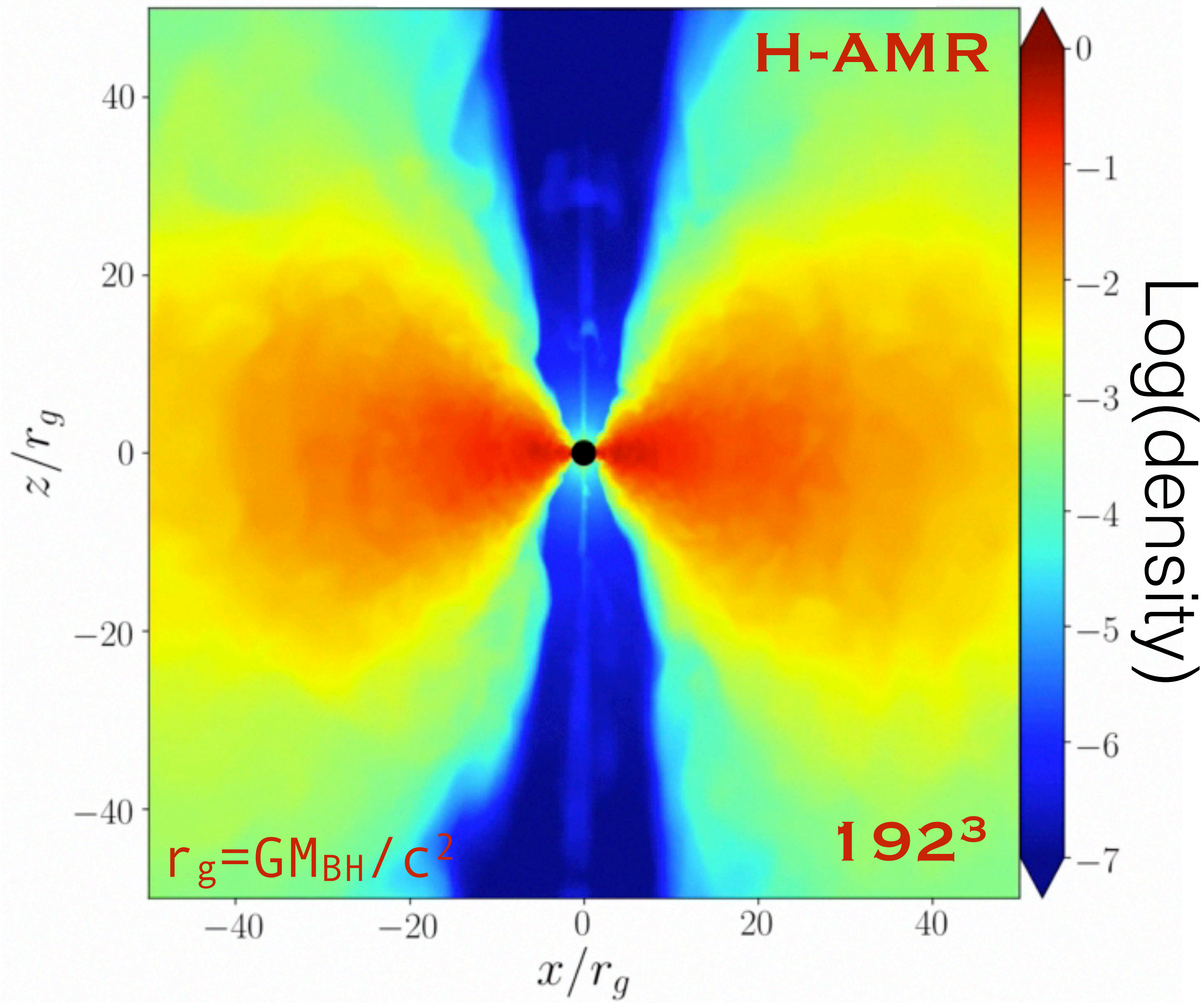
GRMHD simulations of disks and jets

- Fluid Dynamics + Magnetic fields + General Relativity

Setup consists of:

- a central spinning black hole
- a rotating disk of gas
- weak magnetic fields in the disk

e.g., Porth, **Chatterjee**+19

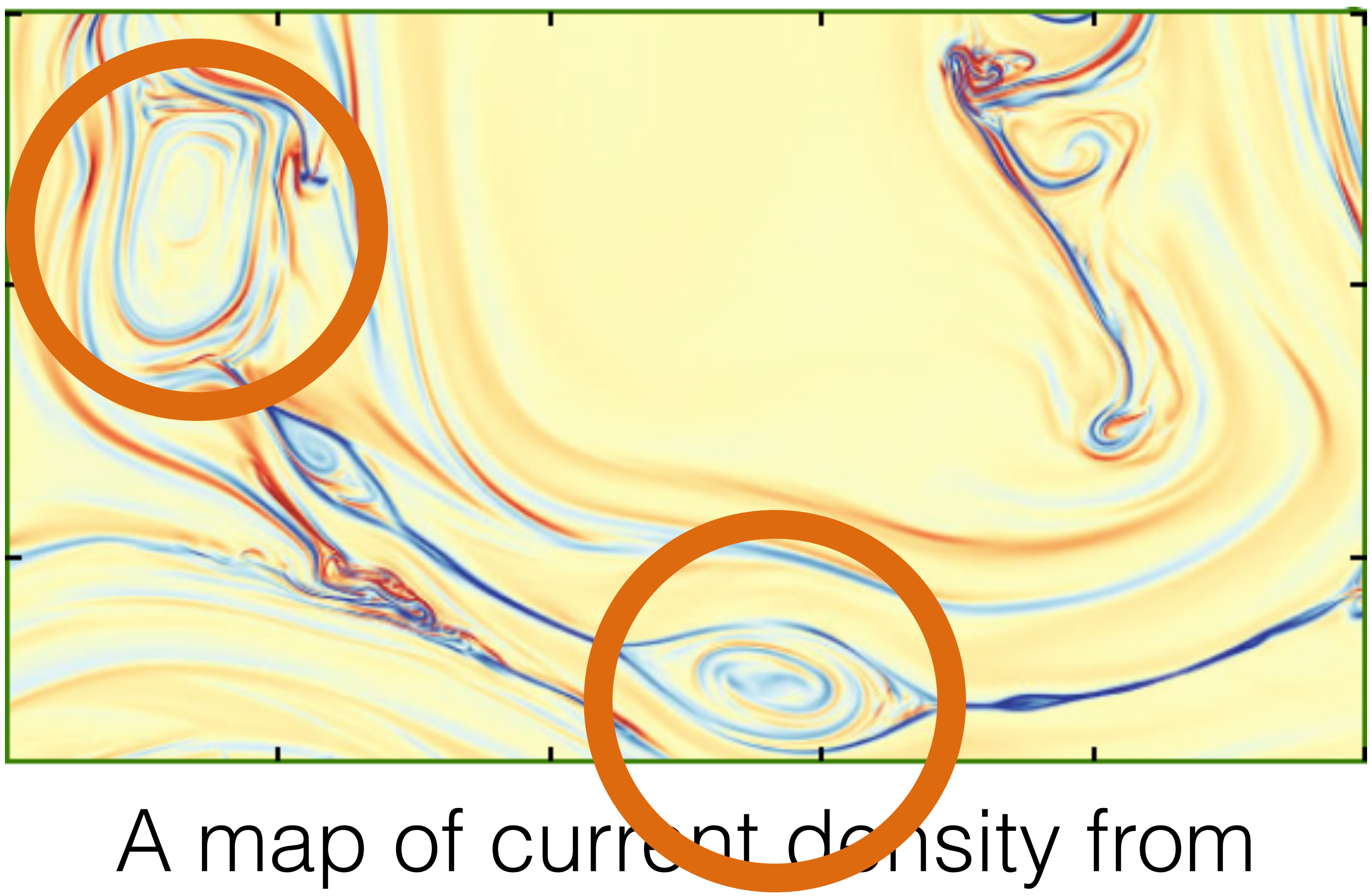


H-AMR: a GPU-accelerated GRMHD code (Liska+18):

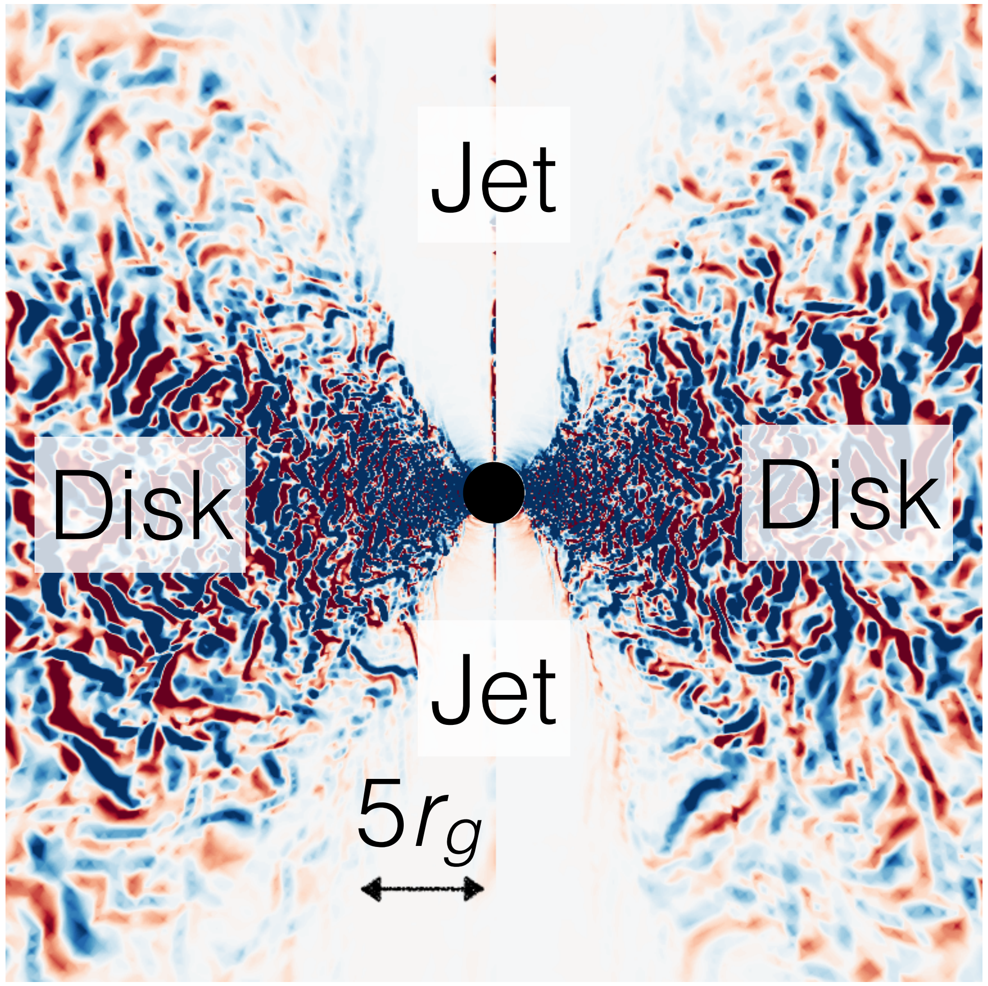
with advanced features like adaptive mesh refinement and local adaptive time-stepping-> allows **>5 orders of scale separation**

So how do we produce non-thermal flaring?

Plasmoids: small blobs of highly magnetised plasma



A map of current density from local MHD simulations: Dong+18



A global GRMHD picture of currents

Highest ever GRMHD resolution: $N_r \times N_\theta \times N_\varphi = 1608 \times 1056 \times 1024$; see Porth, **Chatterjee**+19

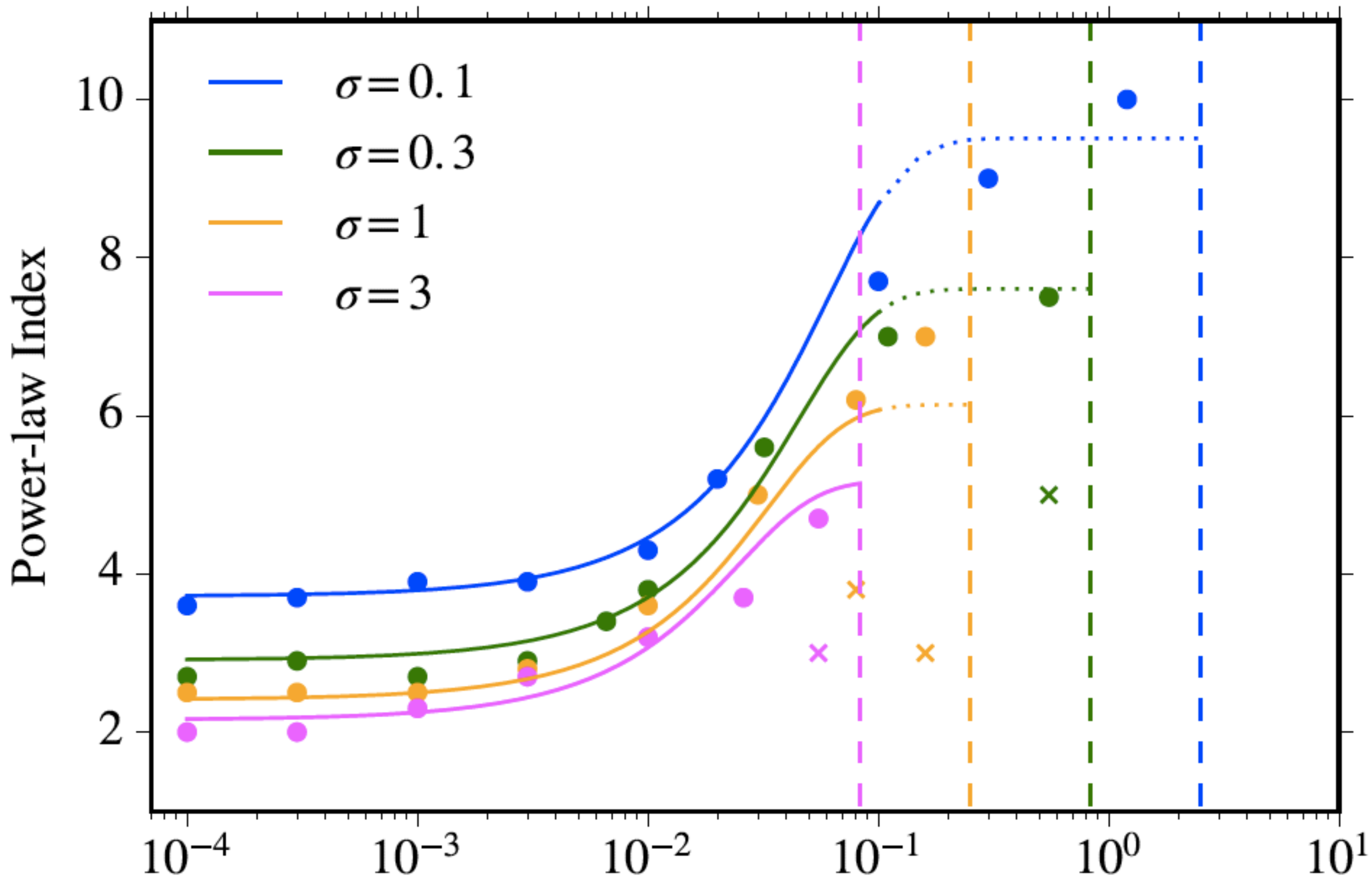
Huge scale separation!

So how do we produce non-thermal flaring?

Particle-In-Cell simulations to the rescue!

Dedicated local simulations to figure out prescriptions for the non-thermal emission efficiency and power-law for **magnetic reconnection**

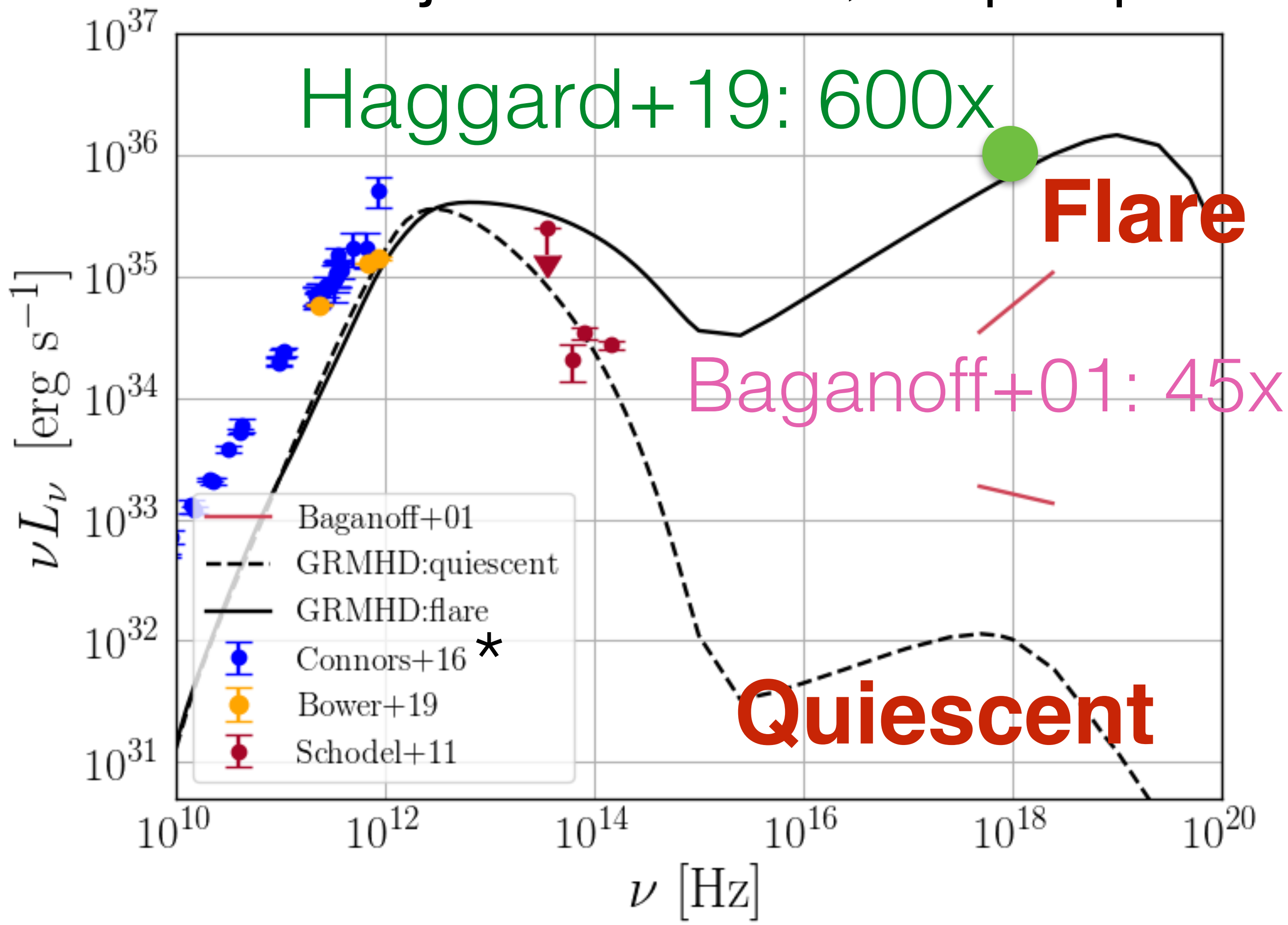
e.g., Ball, Sironi, Özel 2018

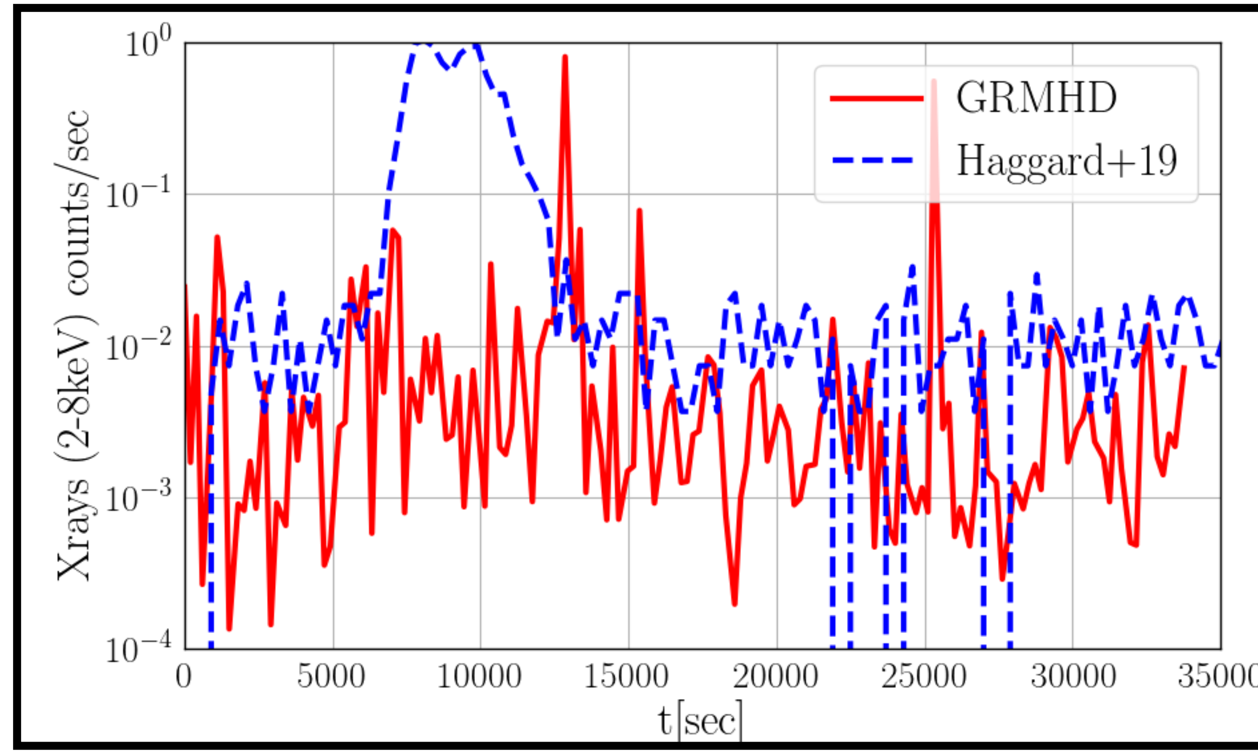


Plasma-beta=P_{gas}/P_{mag}

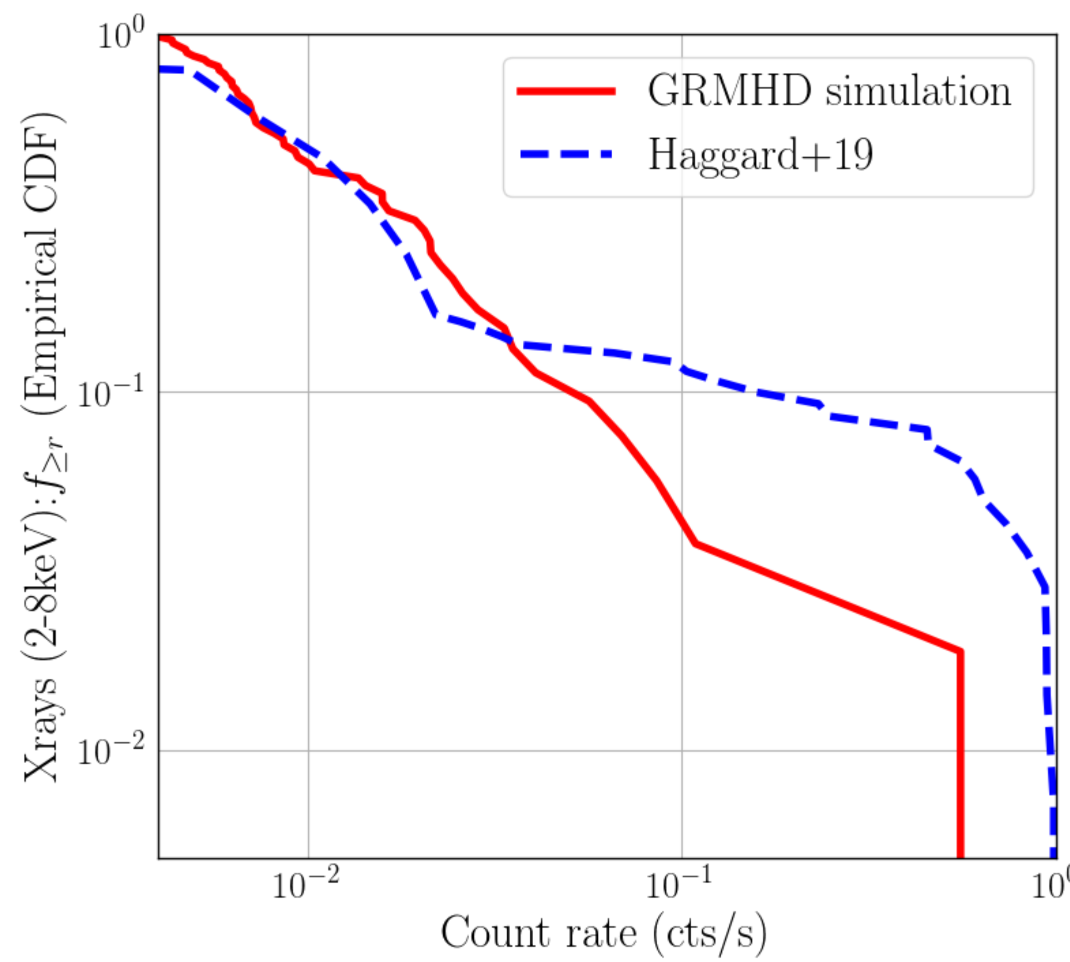
Sgr A* flares from particle-in-cell prescriptions

Chatterjee+2020b, in prep



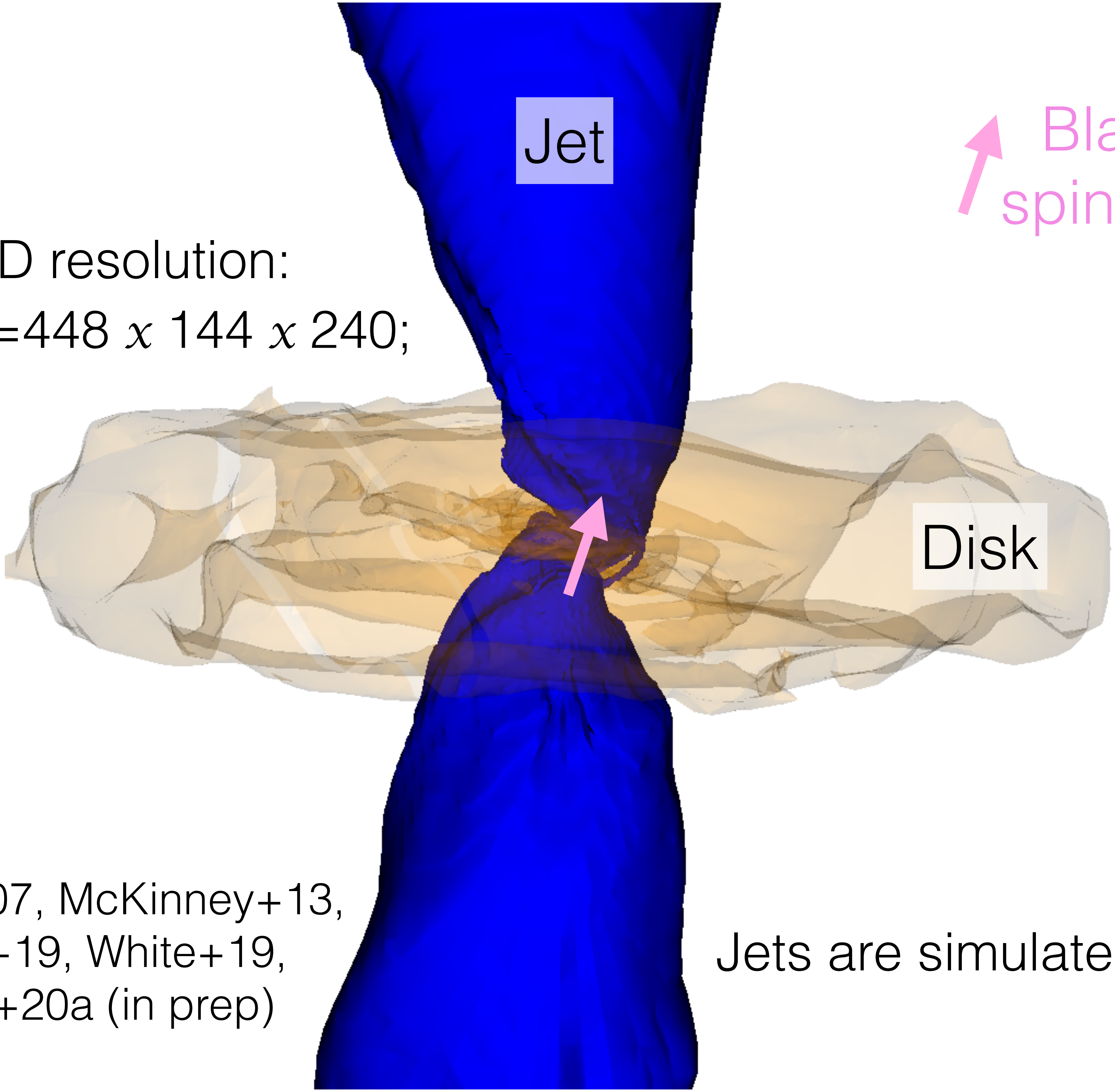


We are coming close, but there is still a lot to do!



* data compiled from Zhao+01, Serabyn+97, Zylka+95, Nord+04, Falcke+98, Roy+04, An+05, Lu+11, Brinkerink+15, Bower+15

Misaligned disks & jets: a new frontier

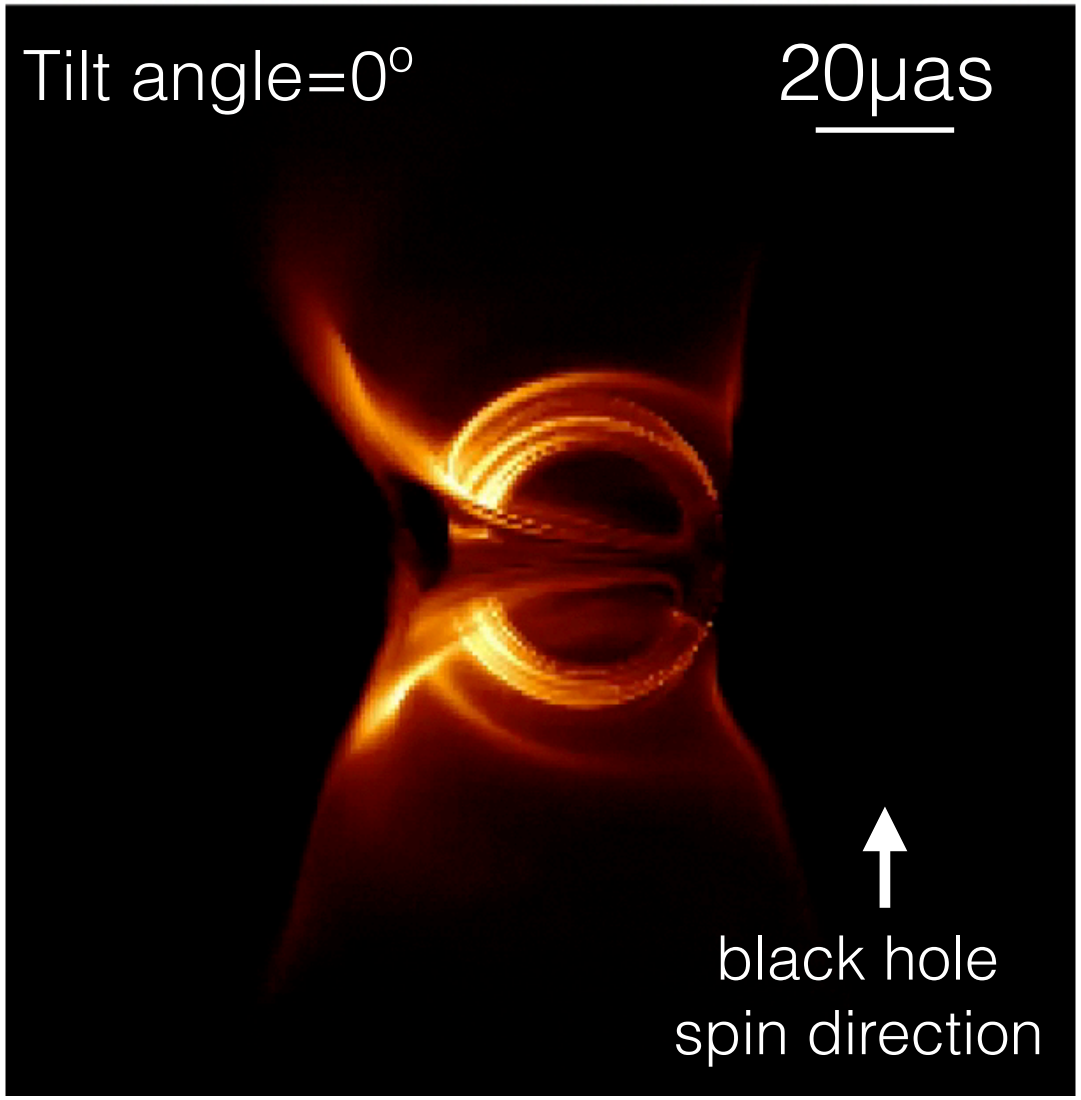


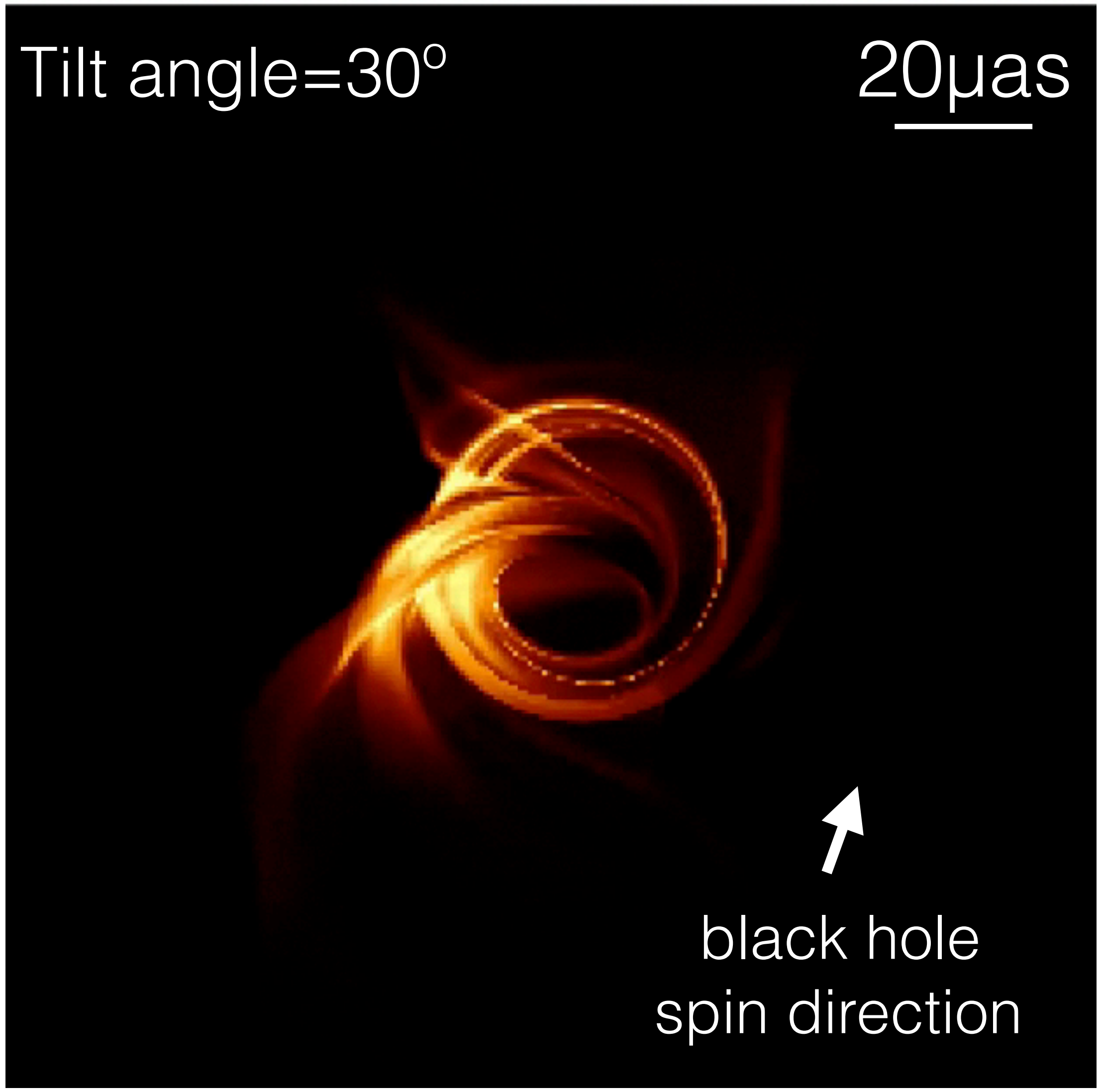
GRMHD resolution:
$N_r \, x \, N_\theta \, x \, N_\varphi = 448 \, x \, 144 \, x \, 240$;

e.g., Fragile+07, McKinney+13, Liska+18, +19, White+19, Chatterjee+20a (in prep)

Jets are simulated upto $10^5 \ r_g$

Misaligned disks: Edge-on@230 GHz



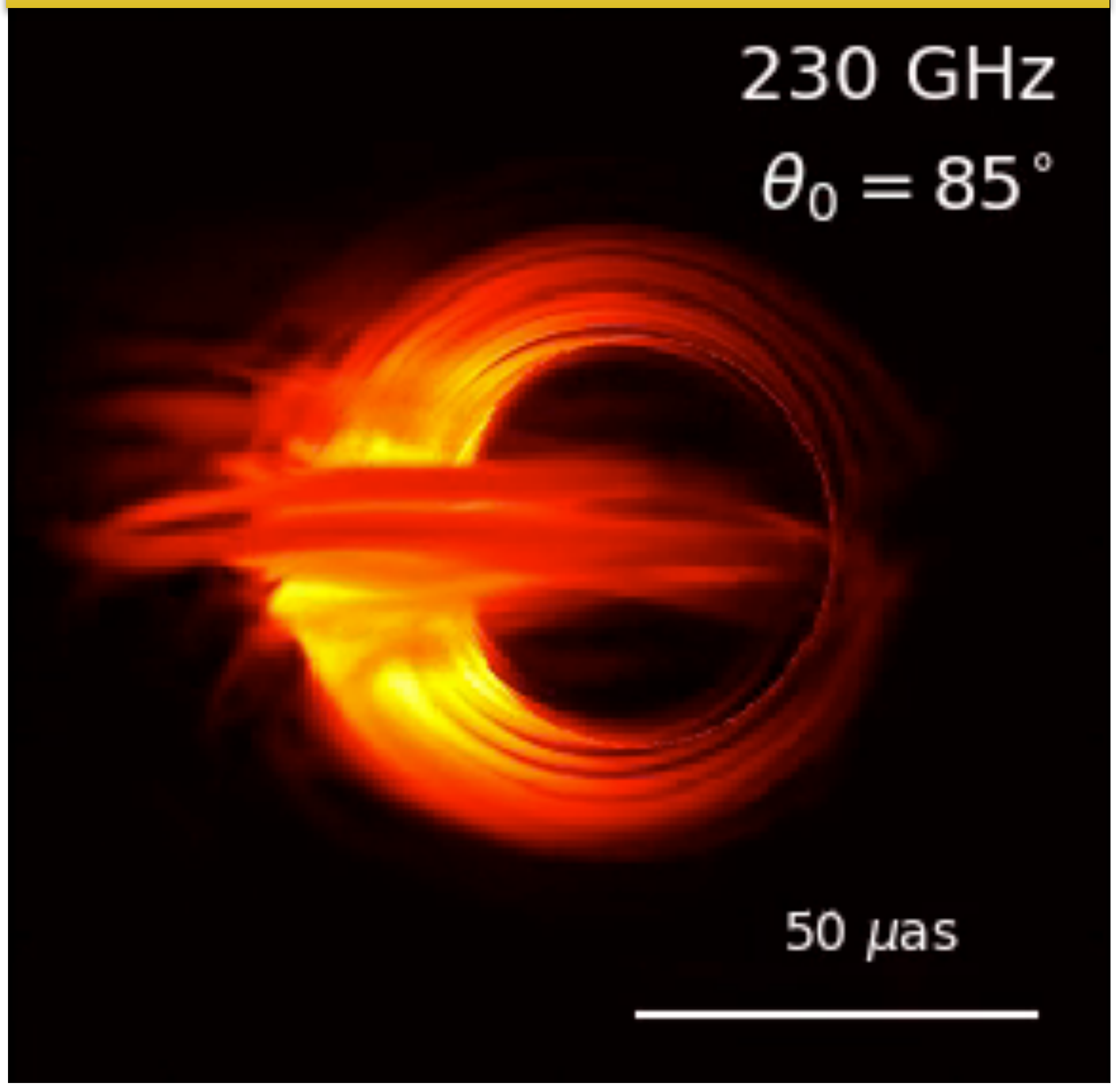


Large scale jet is always pointing up

Chatterjee+20a (in prep), also see Dexter+13

More realistic scenarios…

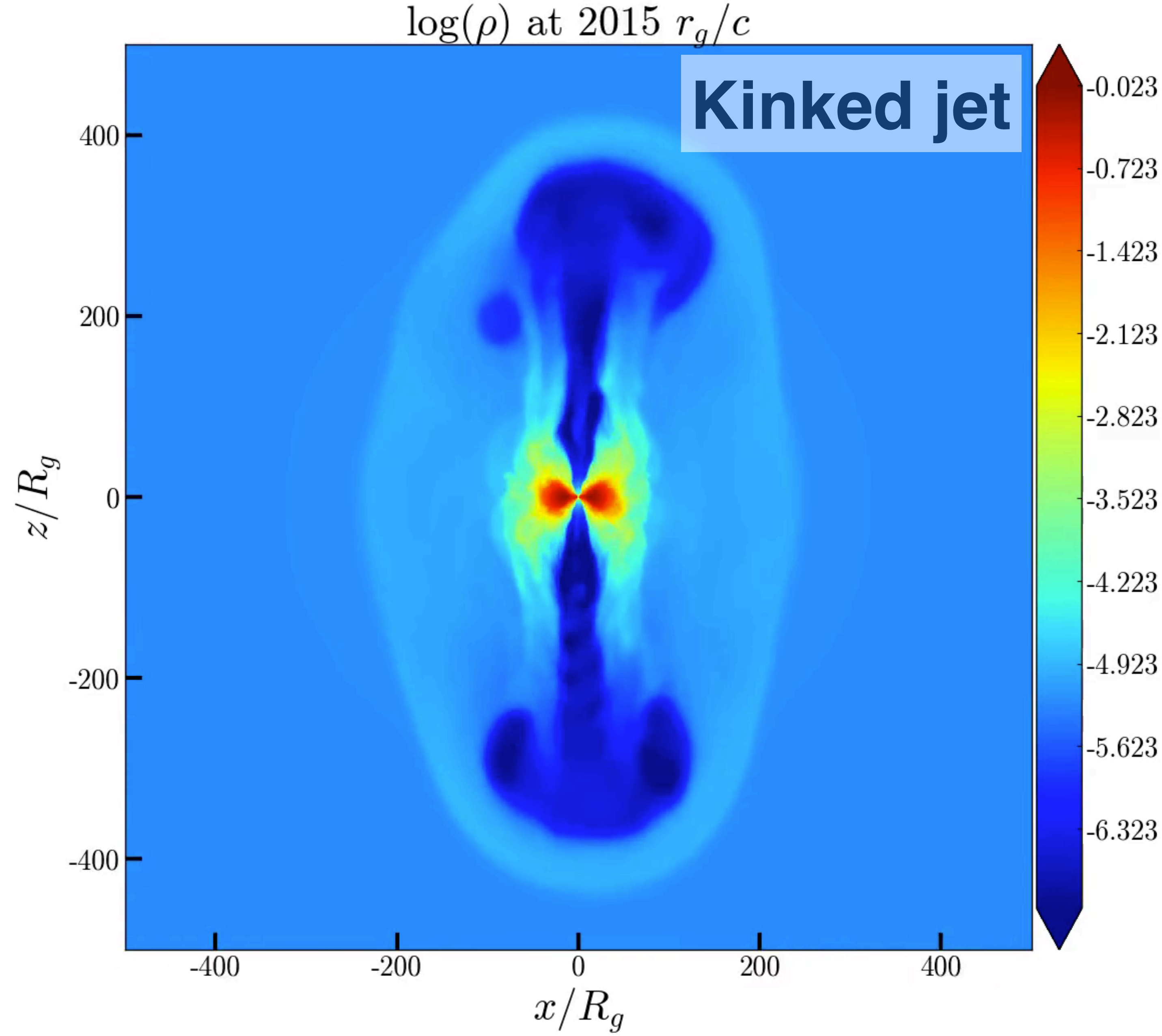
3D radiative cooling:
Yoon, Chatterjee+2019, in prep



Credit: Doosoo Yoon

also see Fragile+09, Dibi+12, Drappeau+13

Kinked and choked jets:
Chatterjee+20, in prep



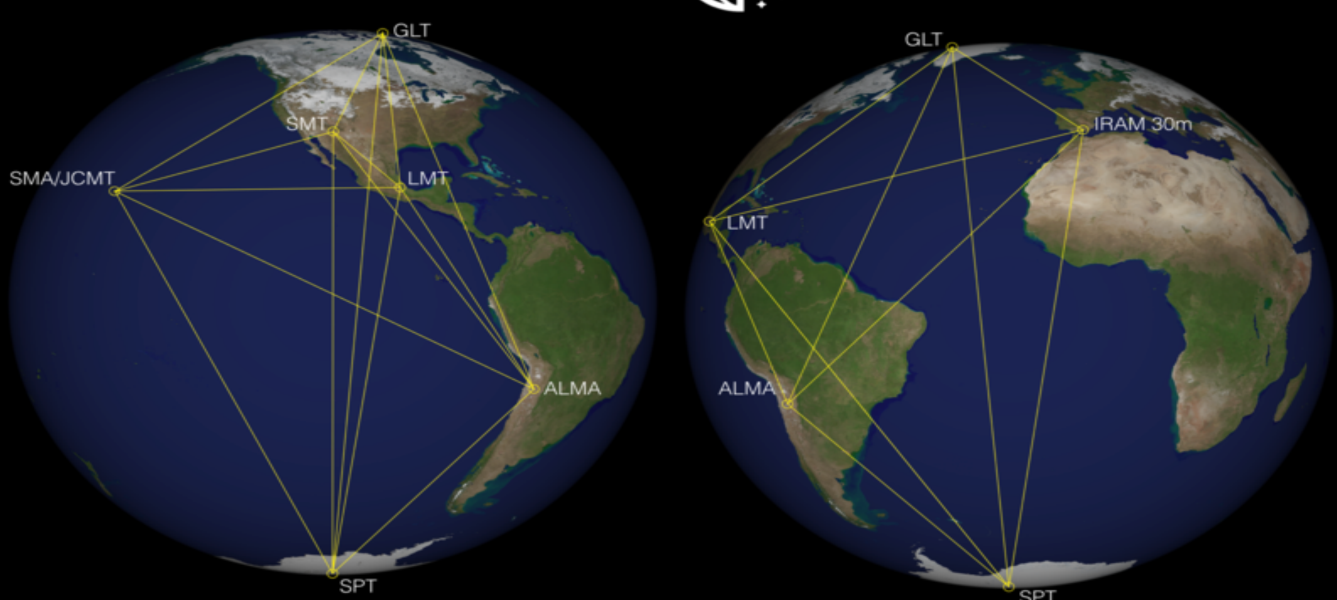
see also Bromberg+16, Barniol Duran+17

Summary: crossing new frontiers with H-AMR

- Simulating black hole disks and jet at **higher-than-ever resolutions** and over **unprecedented spatial and temporal scales**
- **Connecting GRMHD to Sgr A* Flare statistics** is crucial but challenging: all due to exquisite Chandra data
- Considering **Misaligned disks** brings in a rich new parameter space to explore: warping & variability -> Chandra can detect shocks/reconnection events; IXPE for polarisation.

Lots of more physics to add: electron physics, heating and cooling mechanisms, radiation coupling, more realistic environments

Event Horizon Telescope



BLUE WATERS
SUSTAINED PETASCALE COMPUTING

NWO

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