GRMHD simulations of relativistic jets

Main collaborators: Alexander Tchekhovskoy & Sera Markoff

Matthew Liska
University of Amsterdam
Frankfurt seminar 16-02-2016

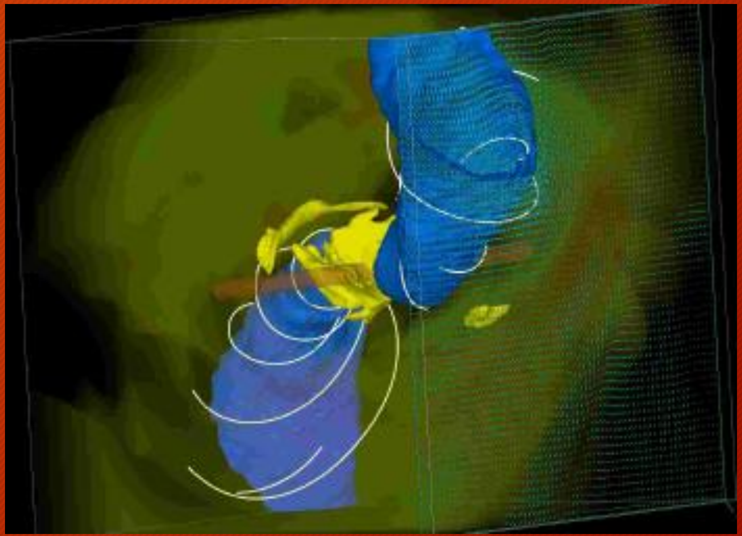
Content

- Introducing a new code: HARM-GPU
- Introduction to AGN jet physics
- Simulations setups
- Results

Trends in astrophysical MHD

- Use fewer assumptions/include more physical effects
- Resolve all relevant distance scales in 3D simulations
- Study systems over multiple orders of magnitude in time
- We need high performance MHD codes to move on!


Credit: SCO


Credit: McKinney, 2012

New code: HARM-GPU

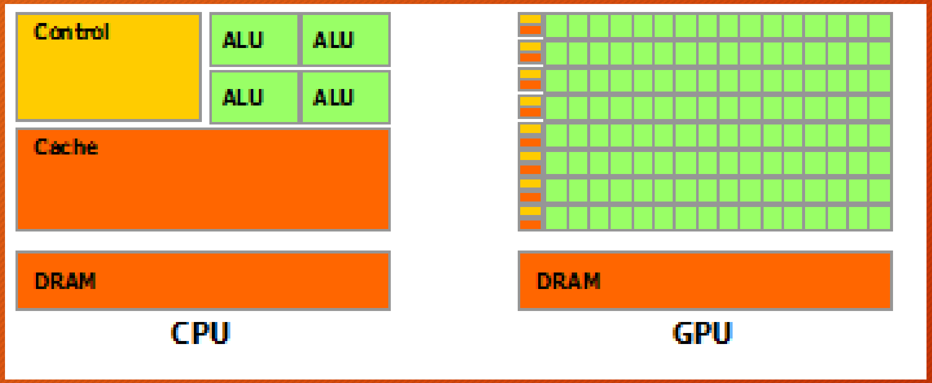
- Based on well tested HARM GRMHD code
- Makes use of GPUs
- Various algorithmic enhancements such as better numerical solvers (HLLC) and staggered grid in work
- Adaptive grid will be implemented as well

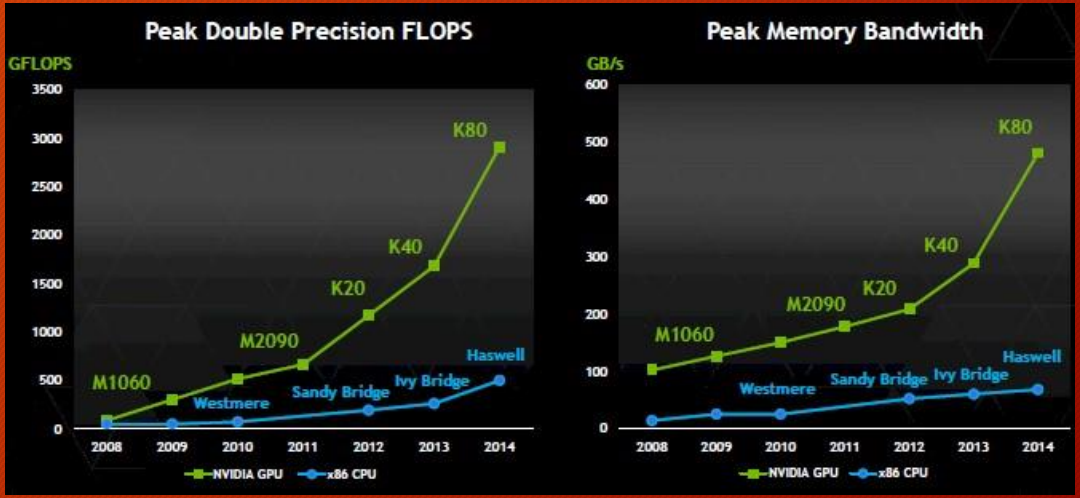
Why GPUs

- Non vectorised single core performance reached state of perfection in CPUs and accelerators
- Speedup lies in more cores and use of vectorization for CPUs/Accelerators
- Vectorization is very difficult in HARM (20.000 instructions per cycle)

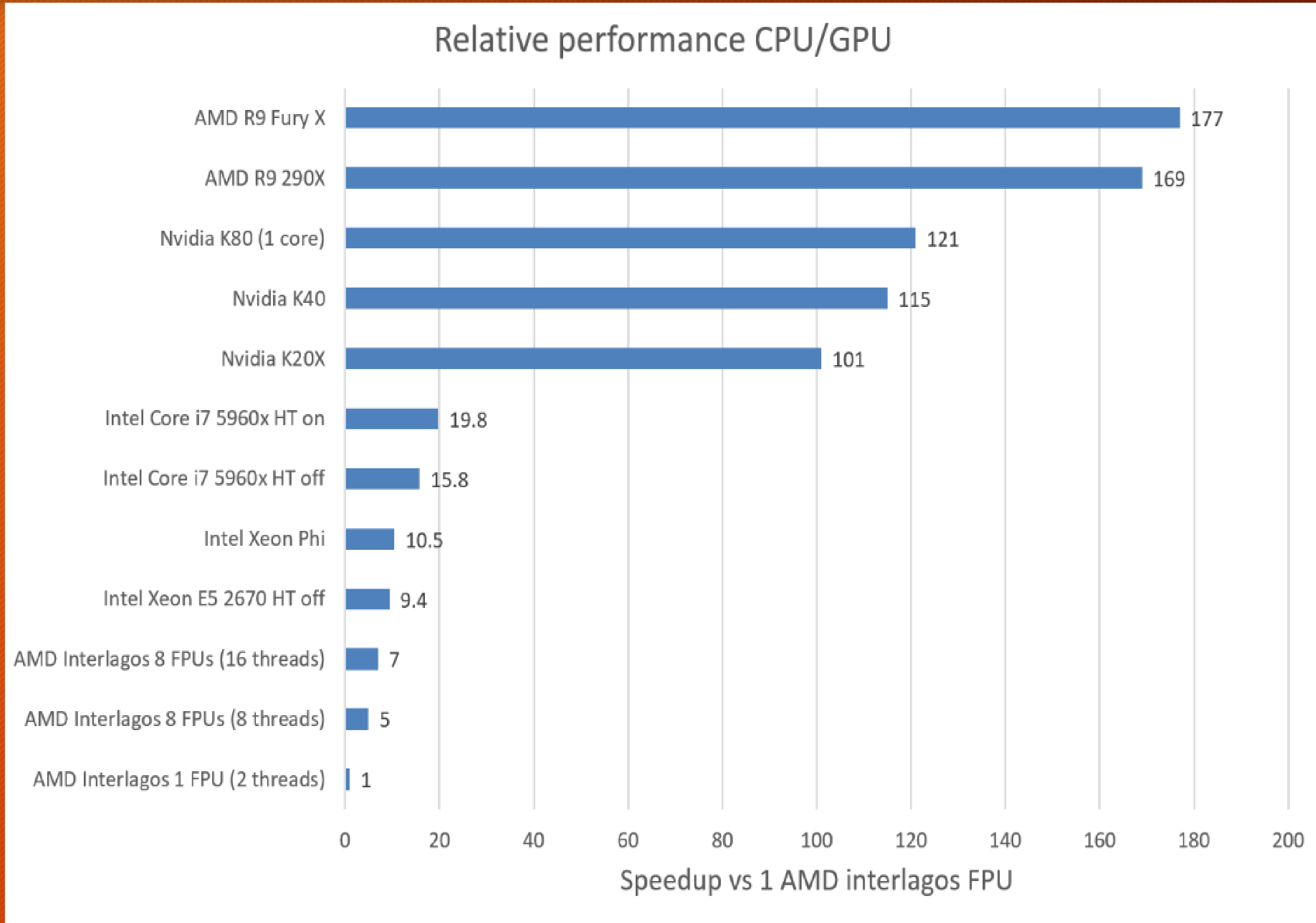
How do GPUs work?

- Goal is not to complete a single task very fast, but 10^5 -10^7 tasks
- Trade circuitry/cache space for more ALU space, but retain huge register size
- Rely on 10+ threads per core to keep stream processors busy
- Necessitates usage of specialised programming languages (OpenCL/CUDA)

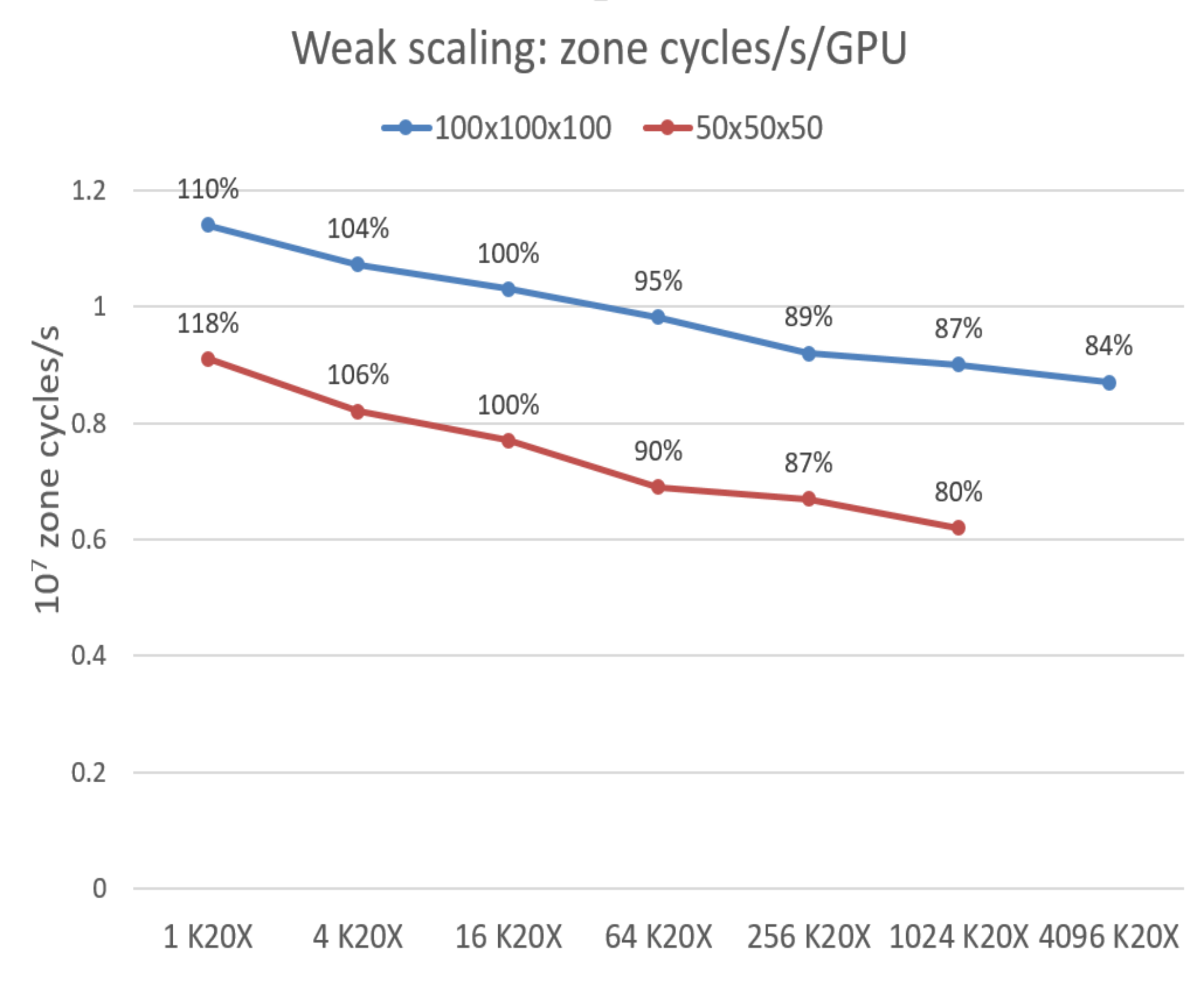




Code performance



Code scaling

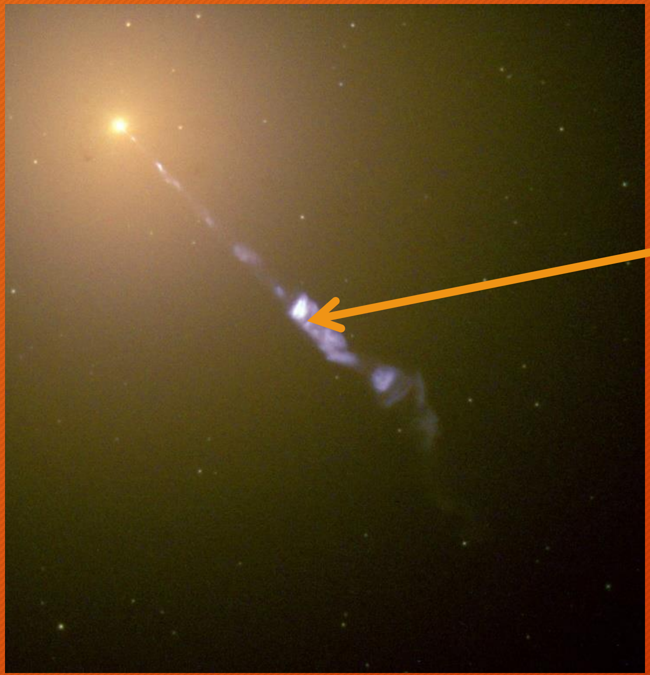


My goal: Understanding jet acceleration

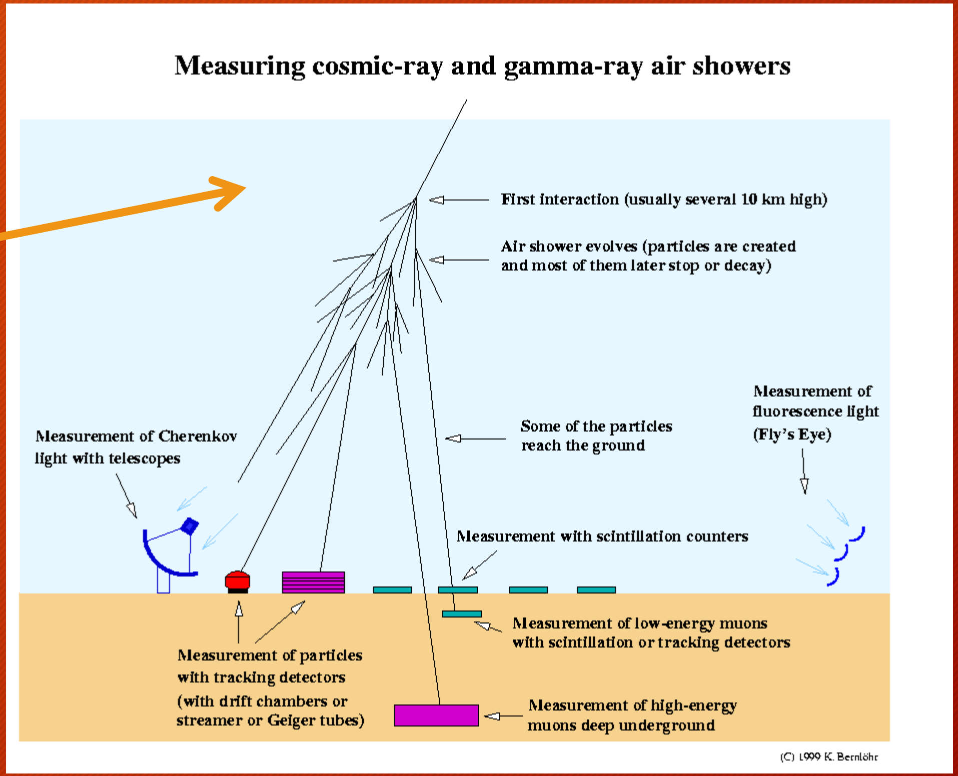
- Jets convert their magnetic energy (Poynting) flux into mass-energy flux through acceleration, but how and on which scales?
- What is the effect of the ambient medium on jet acceleration and shape?

Applications: Cosmic Rays

- AGN jets could be a significant contributor to extragalactic cosmic rays and neutrinos (CTA/IceCube)

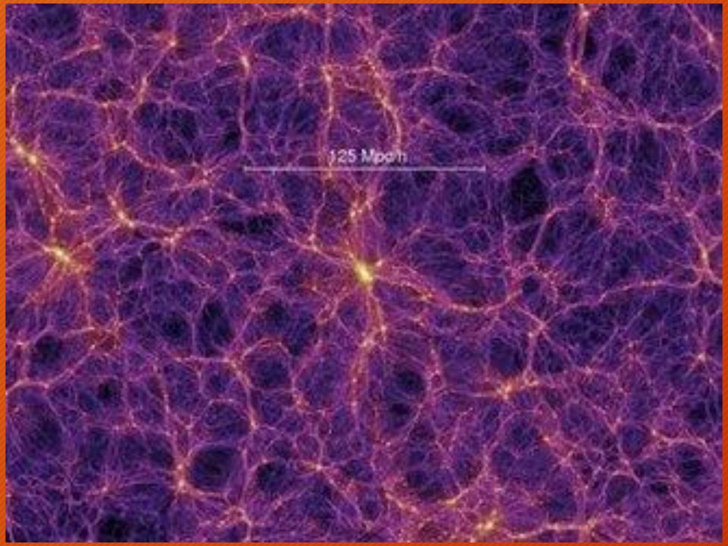


Hubble image of M87
Credit: NASA



Applications: BH feedback

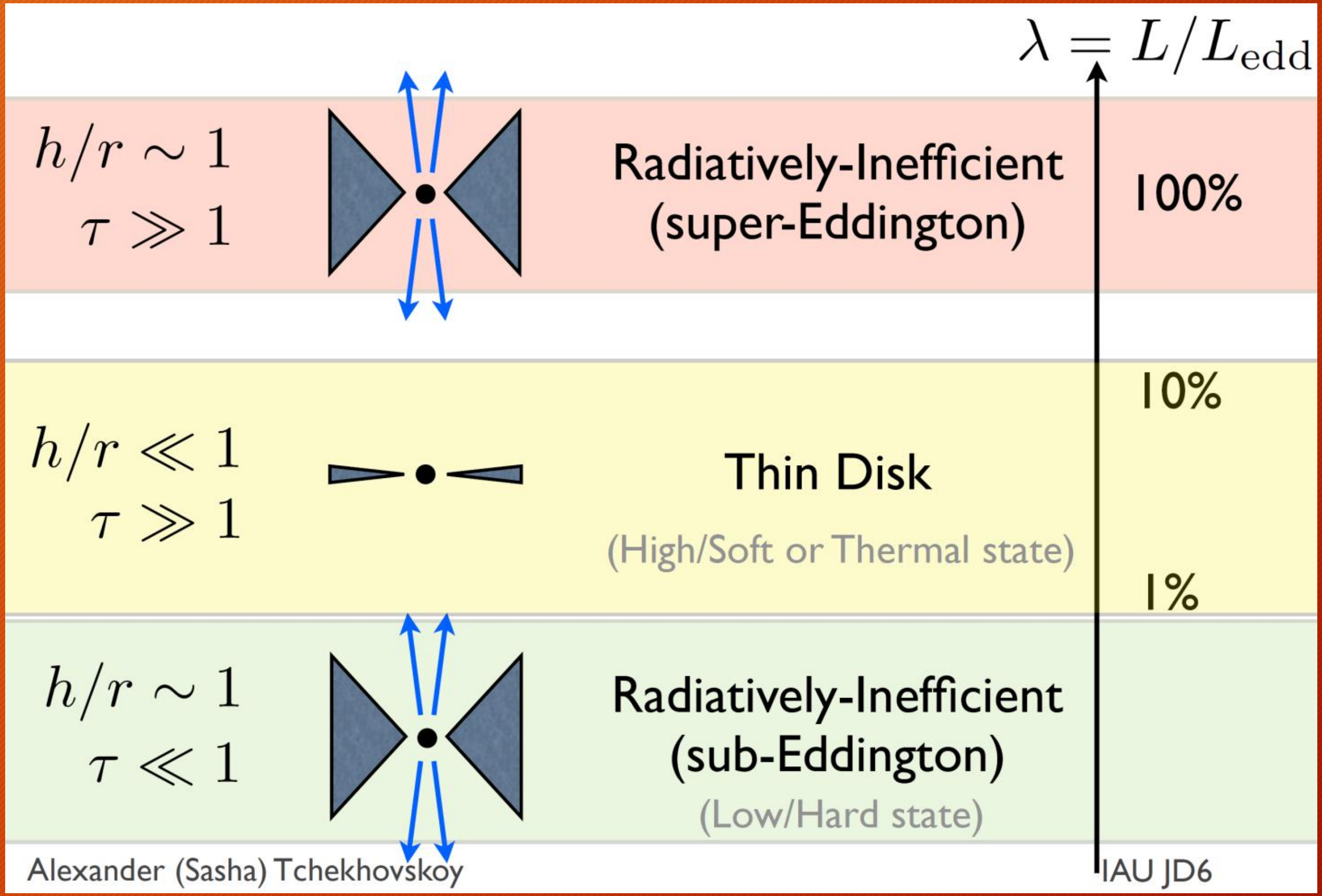
- How do jets influence galactic structure formation?



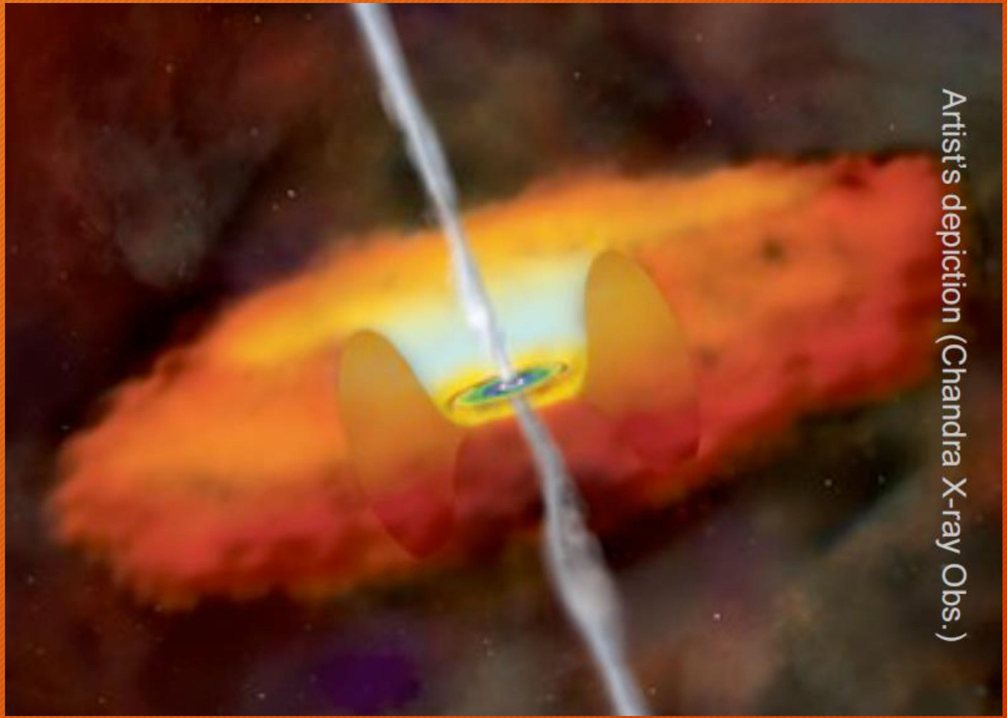
AREPO cosmological simulation

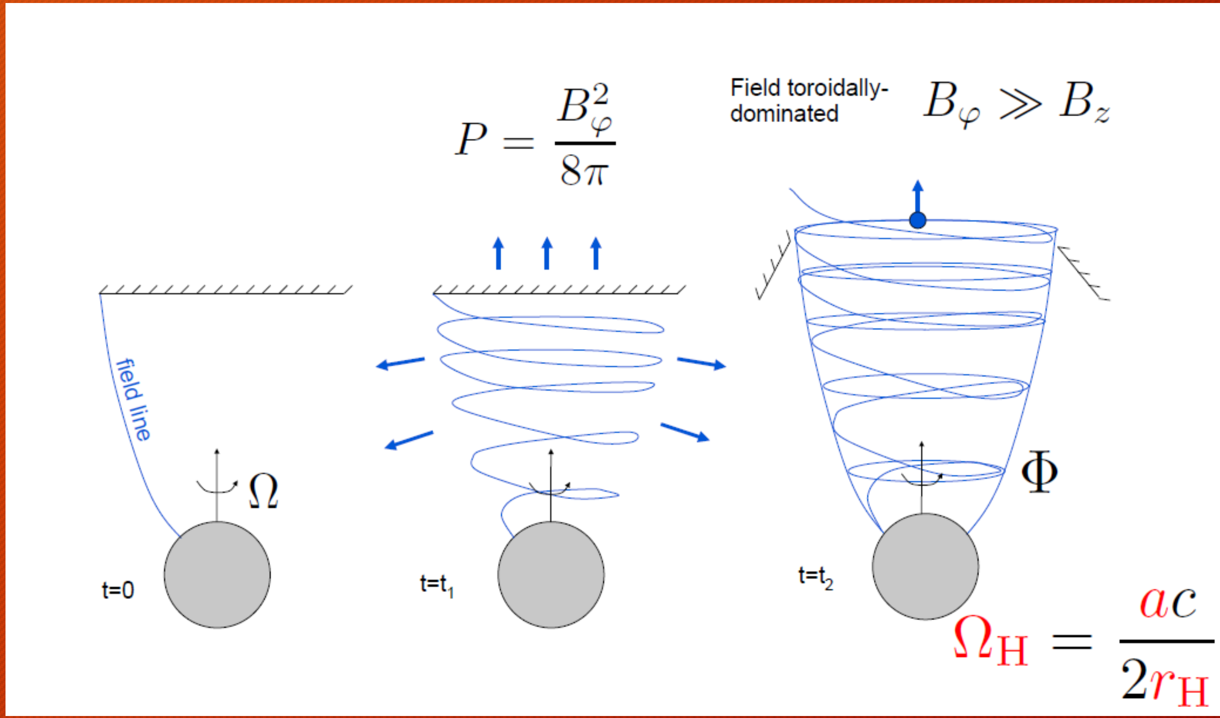
Hubble image Virgo cluster

When are jets launched?



Blandford & Znajek jets

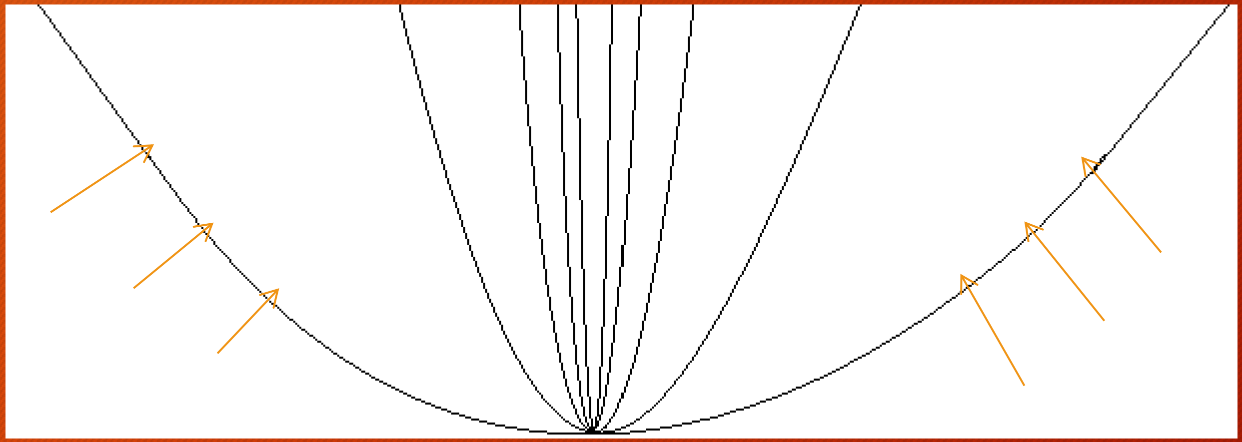




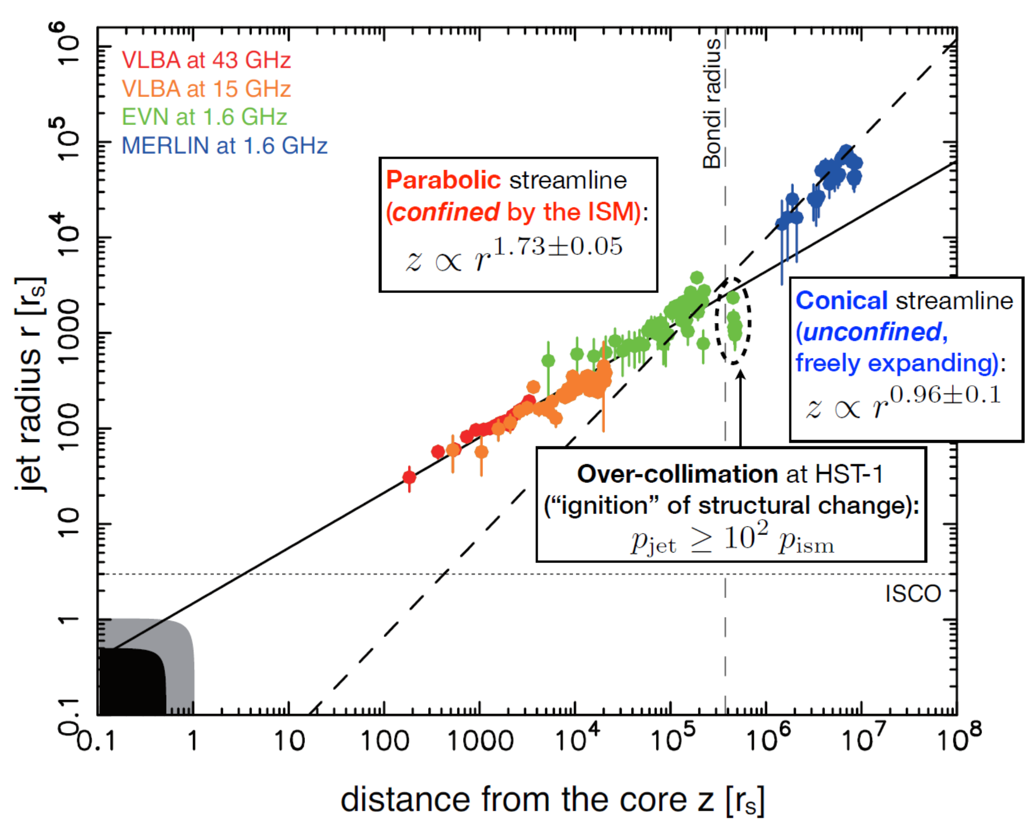
Credit: Alexander Tchekhovskoy

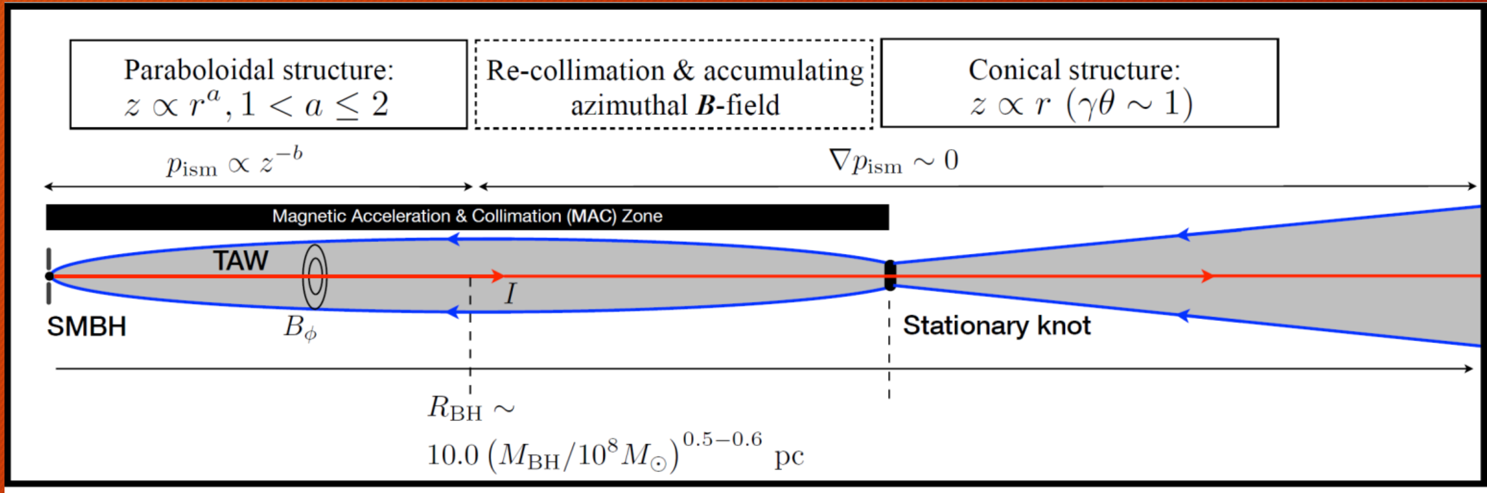
Jet acceleration theory

- Situation a bit different when jets get superfast (v>v_{FMS})
- Conversion of magnetic energy into kinetic energy by reordering of field lines past FMS (fast magnetosonic surface)
- Reproducing a realistic collimation profile in simulations is a challenge



Acceleration and collimation of jets





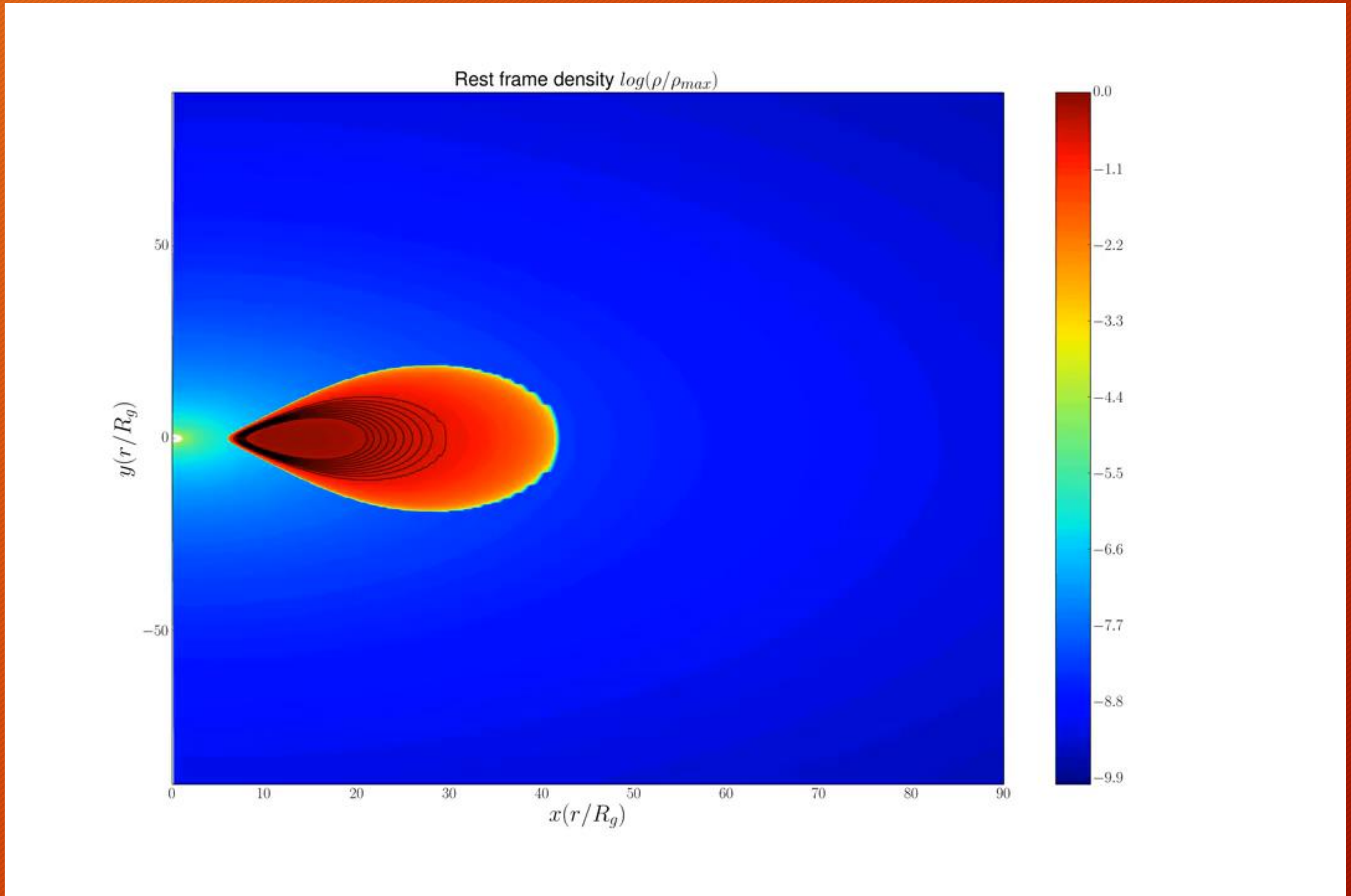
MN & Norman

Credit: Asada & Nakamura, 2012

Simulations

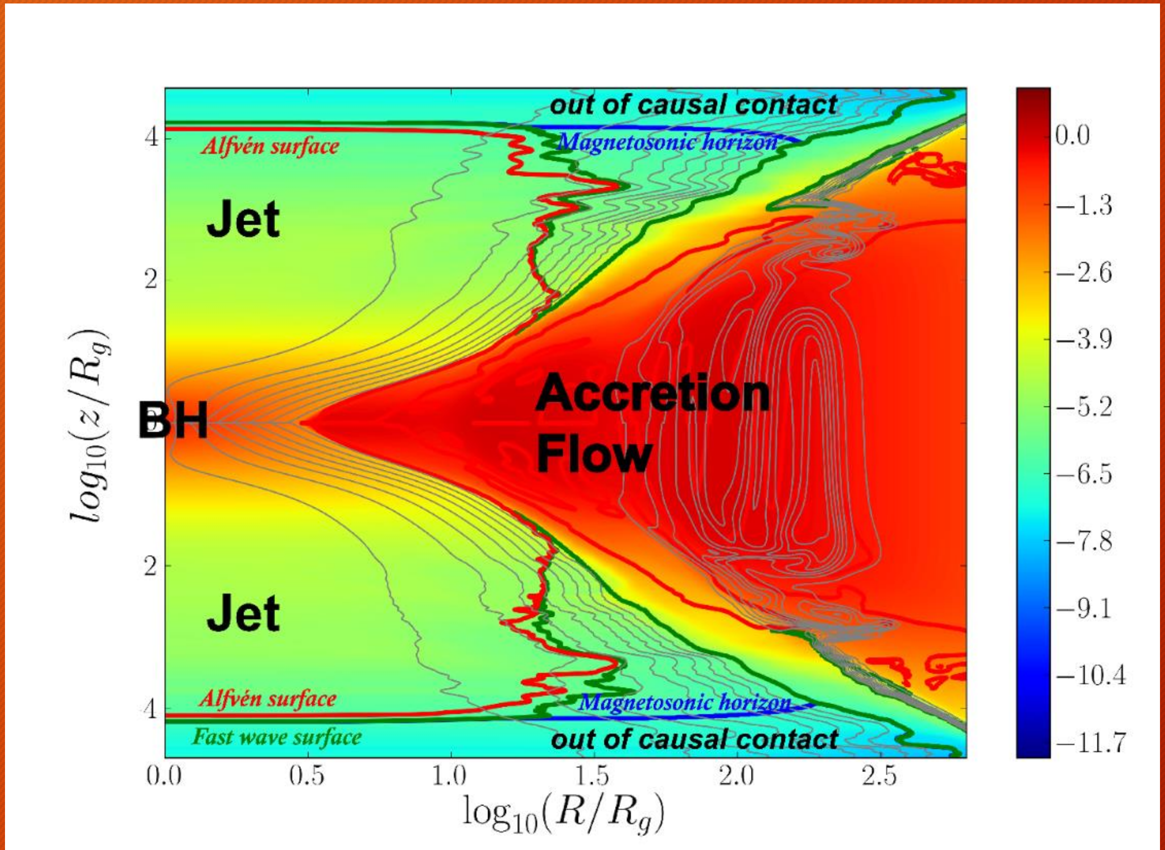
- Assumes a radiatively inefficient sub-eddington rate torus
- Assumes axisymmetric ideal MHD
- Adds viscosity and resistivity through use of Riemann solver (HLL)
- Uses density floors to mass-load the jet
- Uses grids that can resolve the substructure of the jet over 5 orders of magnitude

Movie: Toroidal pinch instabilities forming



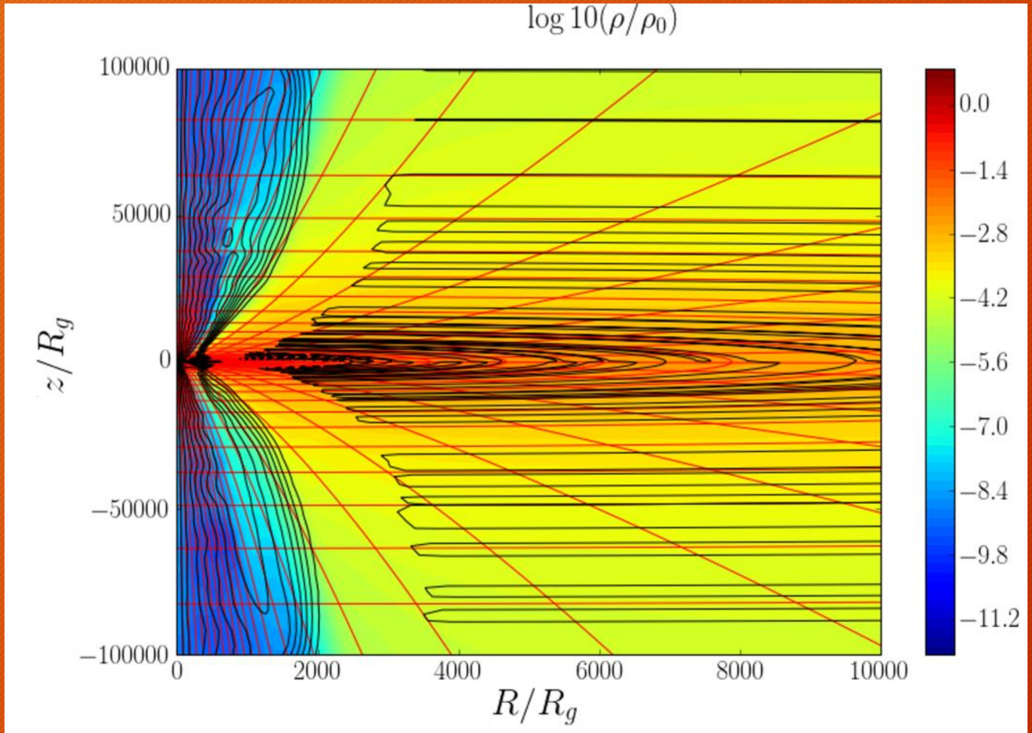
Configuration

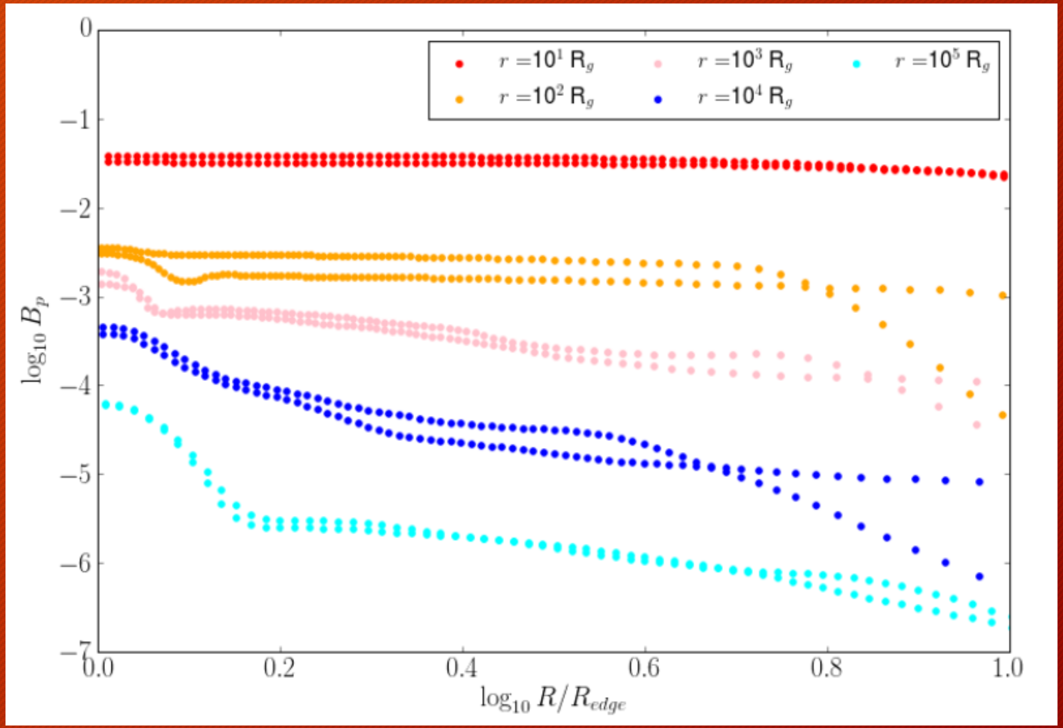
- Giant ADAF extending till the Bondi radius of $5 * 10^5\ R_G$



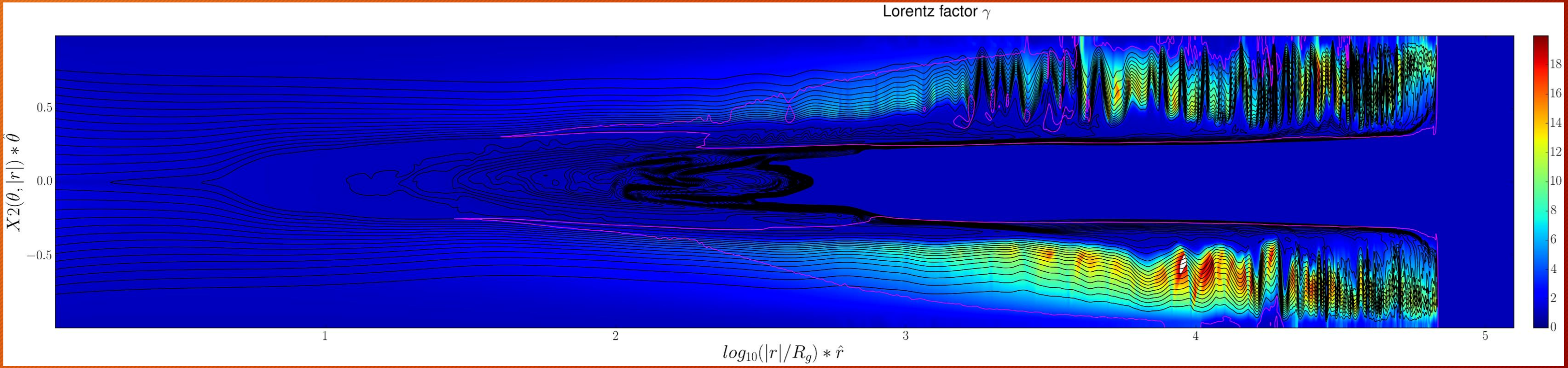
Results: Jet's core resolved properly

- The inner core (cusp in B_p) is resolved due to high resolution focusing of a static grid → Important for differential collimation



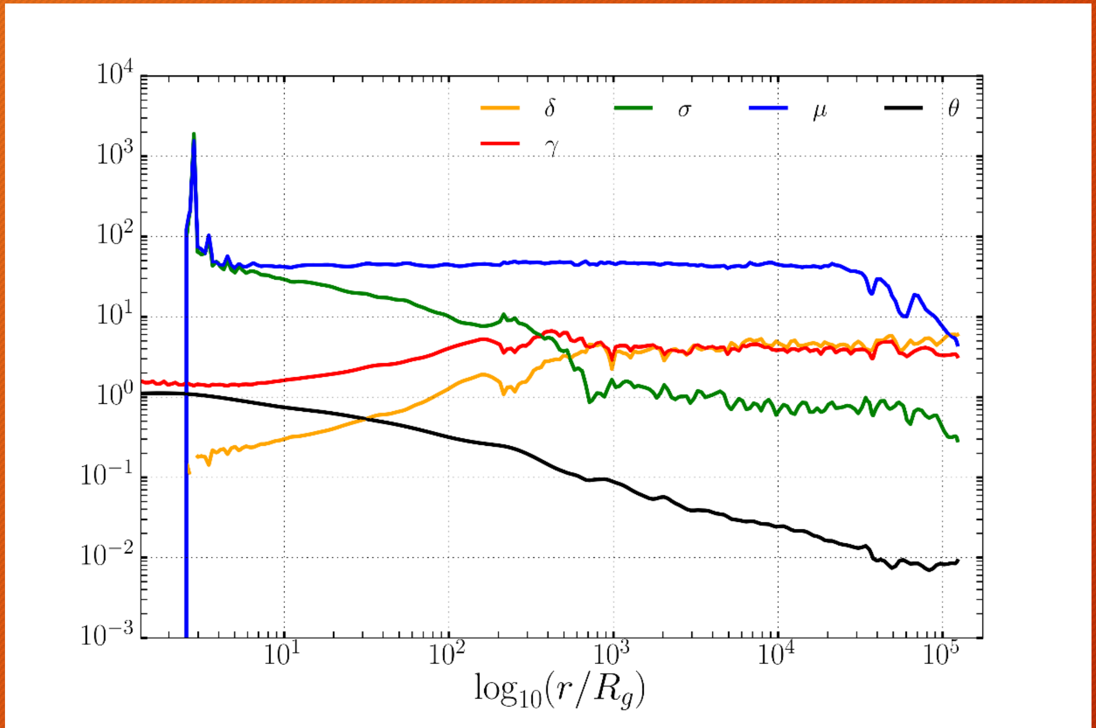


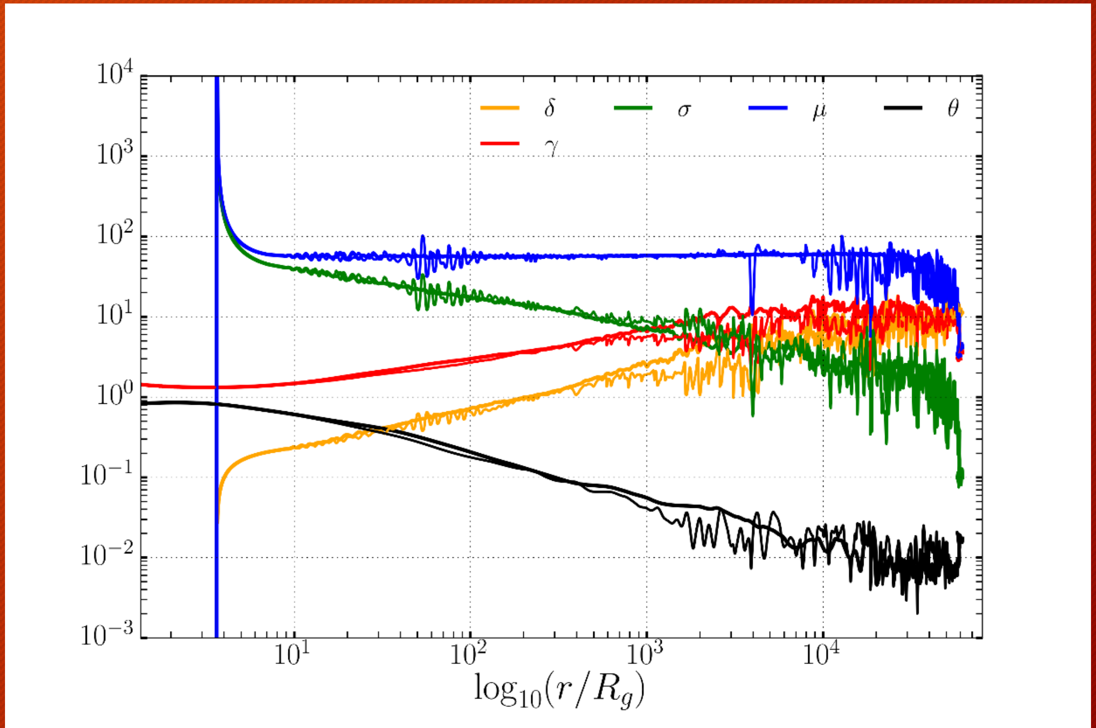
Jet structure



Results: Low res model (left); High res model (right)

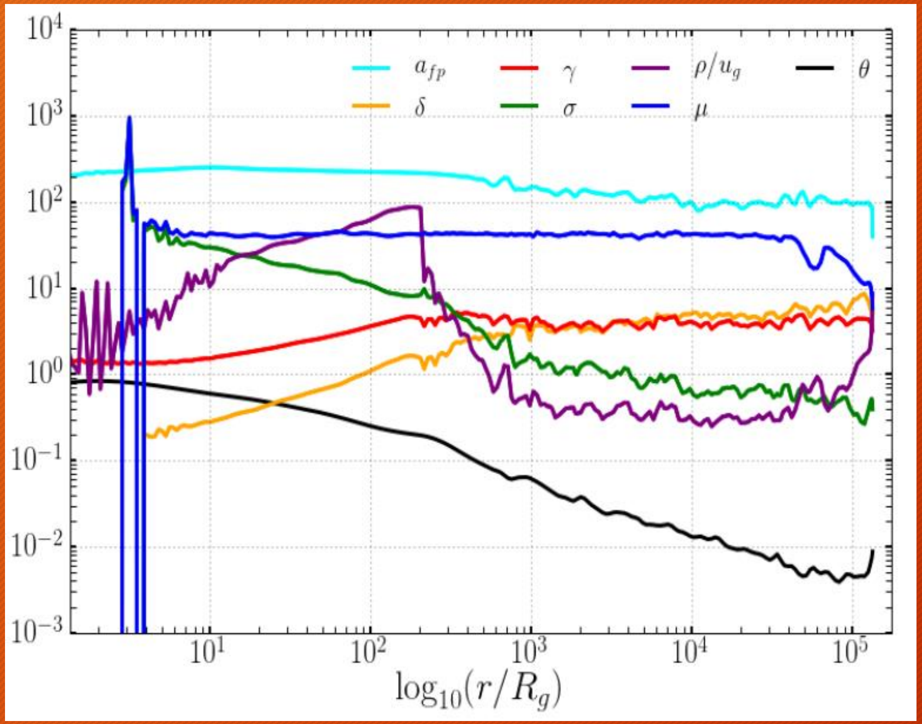
- μ gives the jet's theoretically maximum Lorentz factor γ
- σ gives jet's magnetization
- δ>1 means that the jet's opening angle is larger than it's Mach cone angle

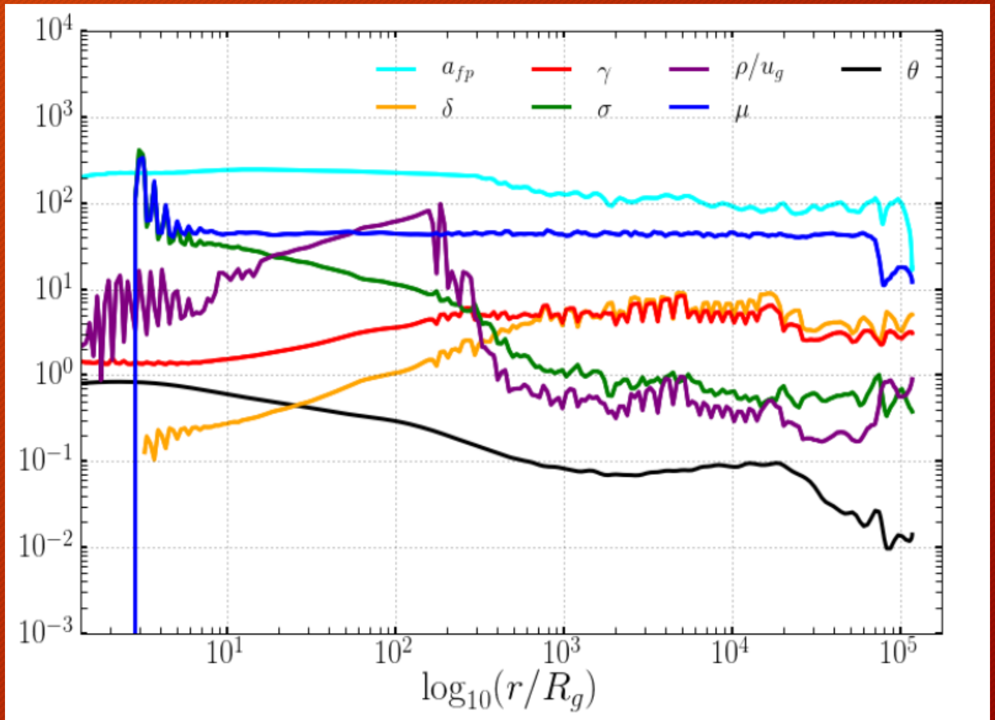




Results: Collimated (left) vs Uncollimated (right)

- μ gives the jet's theoretically maximum Lorentz factor γ
- σ gives jet's magnetization
- δ>1 means a causally disconnected jet

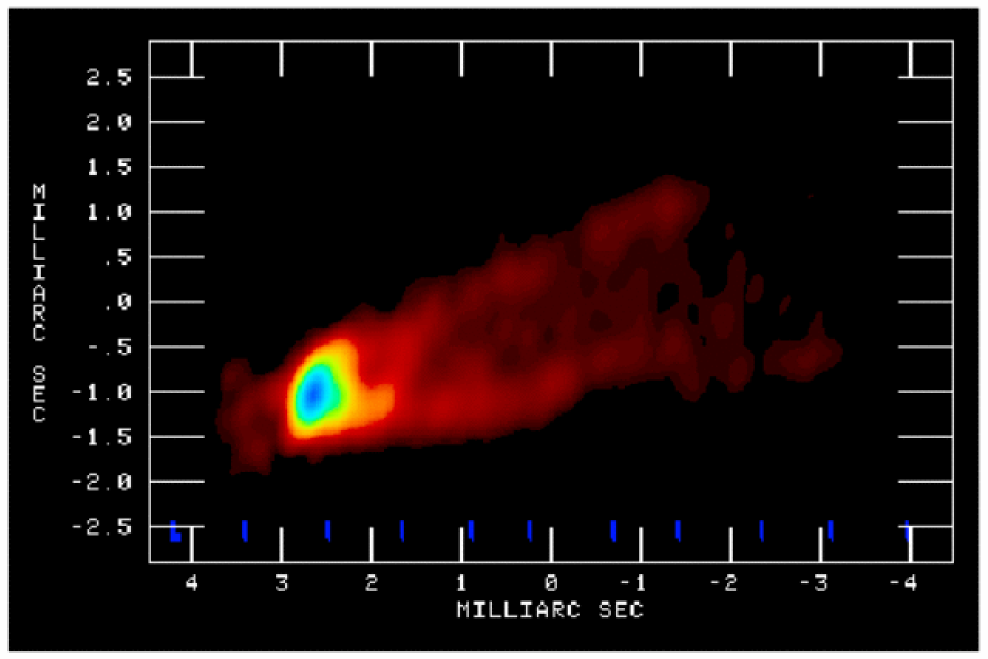




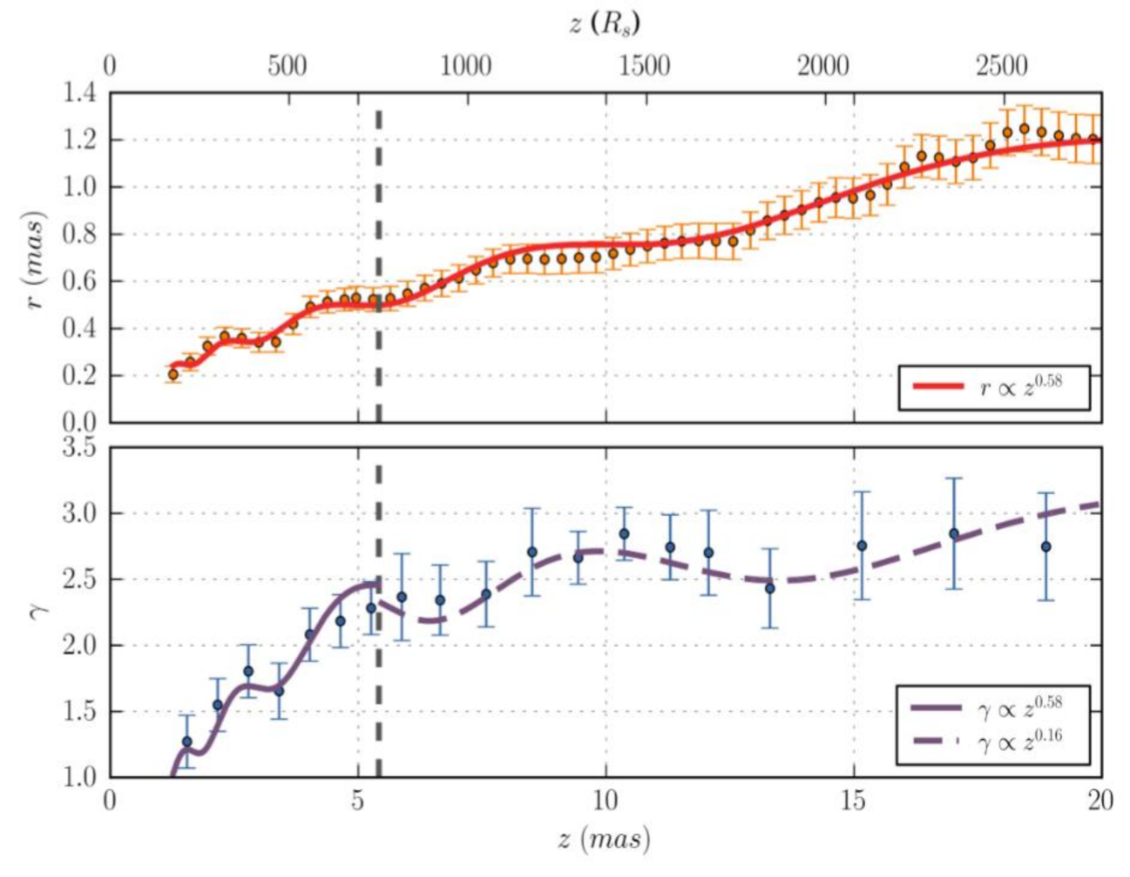
My simulations vs other work

- Idealised models (Tchekhovkoy et al, 2009; Komissarov et al, 2007/2009) show efficient acceleration
- Mckinney et al 2006 observed heating due to toroidal pinch instabilities and found inefficient acceleration
- We observe the same toroidal pinch instabilities but no heat, instead the magnetization is higher and the jet becomes chaotic

Origin of break: Toroidal pinch instabilities?

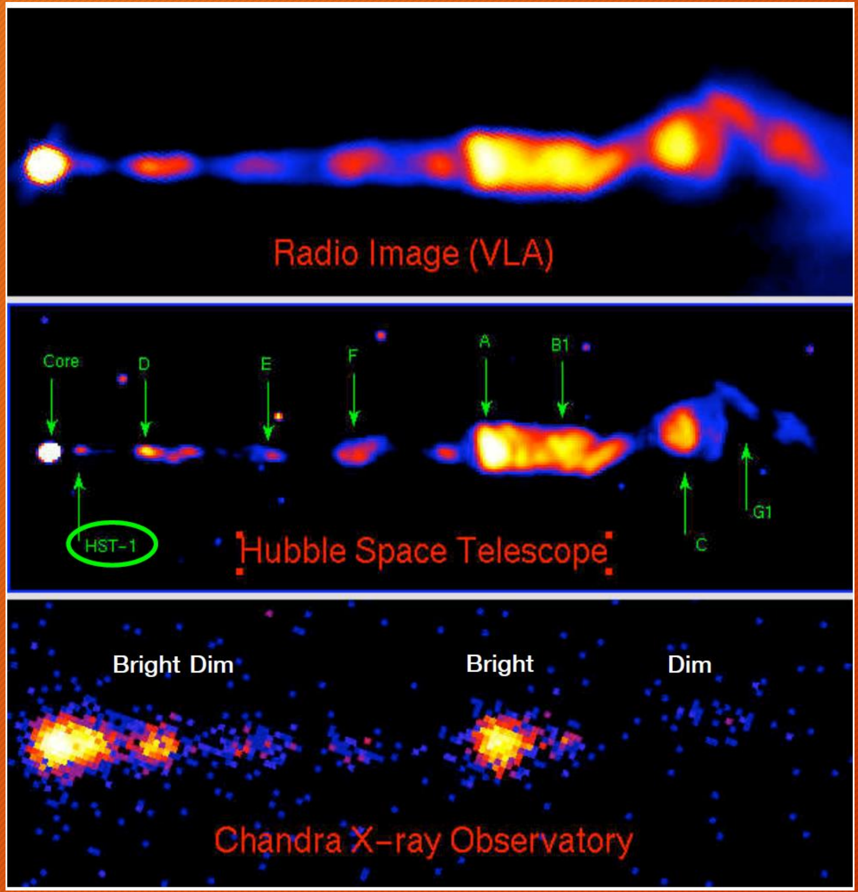


Credit: Walker et al, 2008

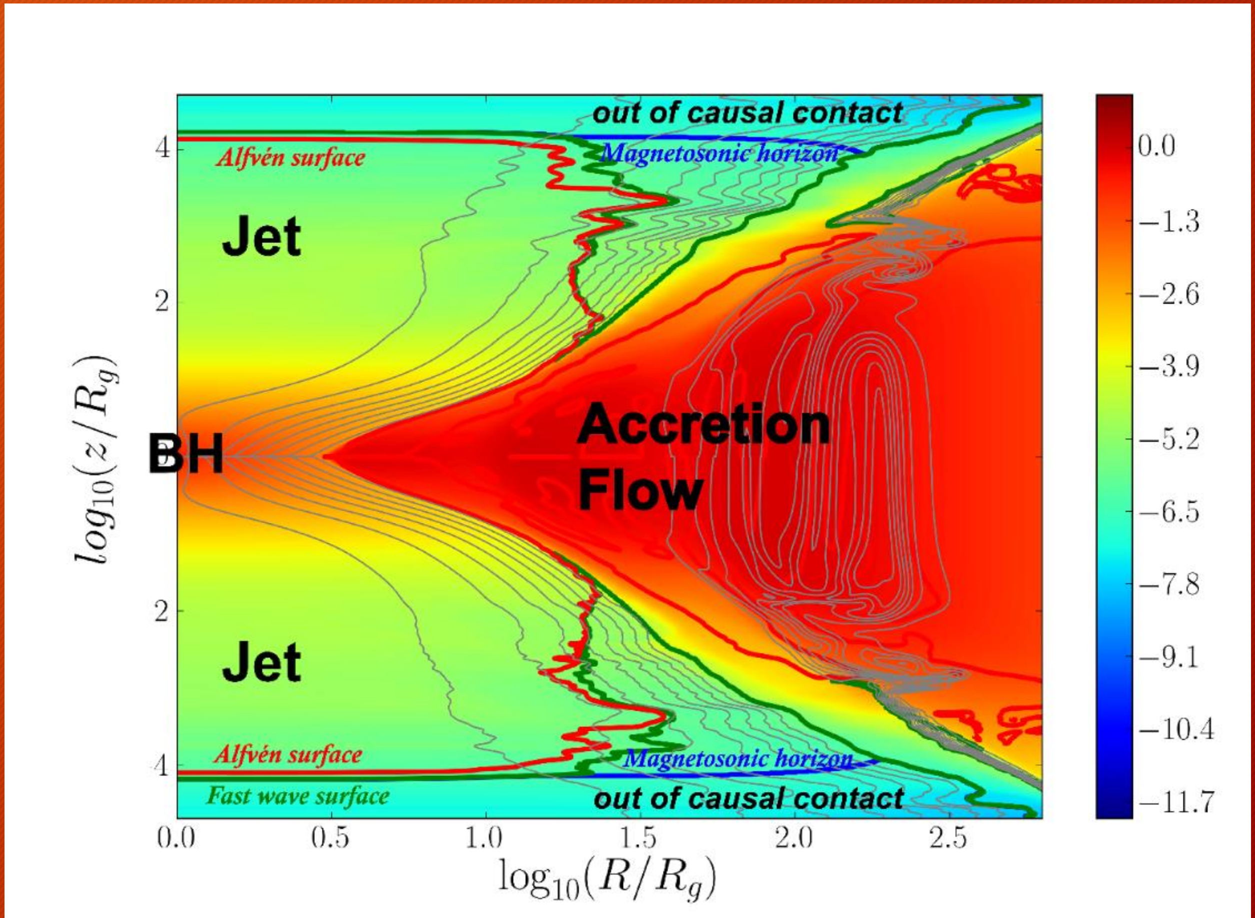


Credit: Mertens et al, in prep

Standing shock features in jets



Credit: NASA



Conclusion

- Axisymmetric jet solutions extended by an order of magnitude in distance due to GPU code
- Highly disordered magnetic field observed
- Toroidal pinch instabilities prevent the jet from accelerating efficiently
- Simulations will be extended to 3D, which is very challenging

Future work: Tilted disk simulations

- Computationally very challenging
- High tilt, long run time and very thin disks most rewarding but highly challenging
- Best opportunity to see (inner) disk precession in combination with alignment of inner disk and black hole
- Resolving the jet is doable as well in 3D
- Tidal disruption event simulations are even more challenging but provide a cleaner result out of first principles