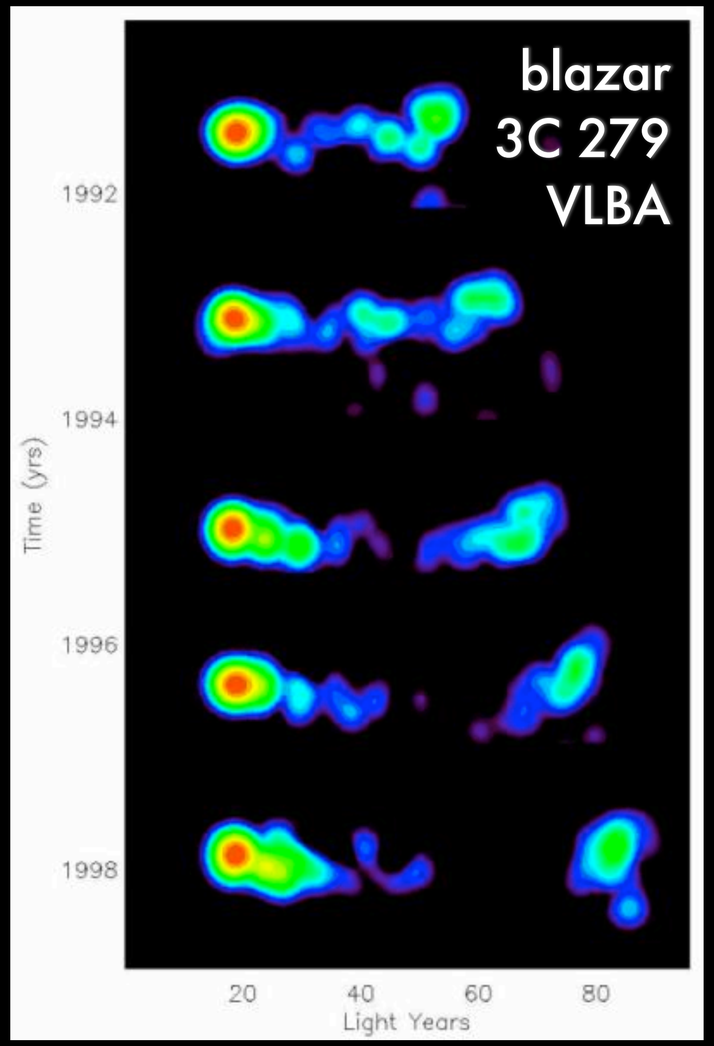
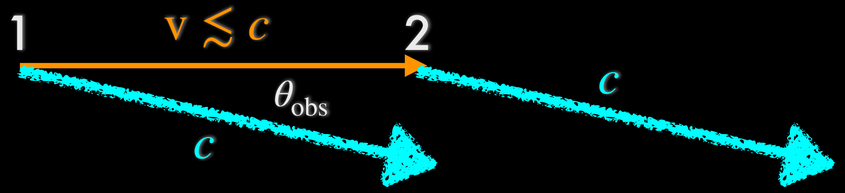
GENERAL-RELATIVISTIC MAGNETO-HYDRO-DYNAMICAL SIMULATIONS OF RELATIVISTIC JETS FROM ACCRETING SPINNING BLACK HOLES

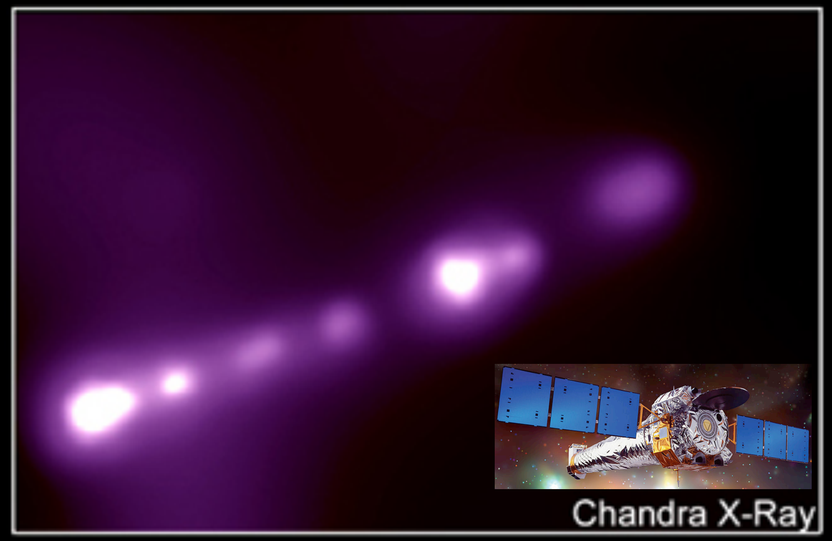
Krzysztof Nalewajko
knalew@camk.edu.pl
http://users.camk.edu.pl/knalew/

apparently superluminal motions

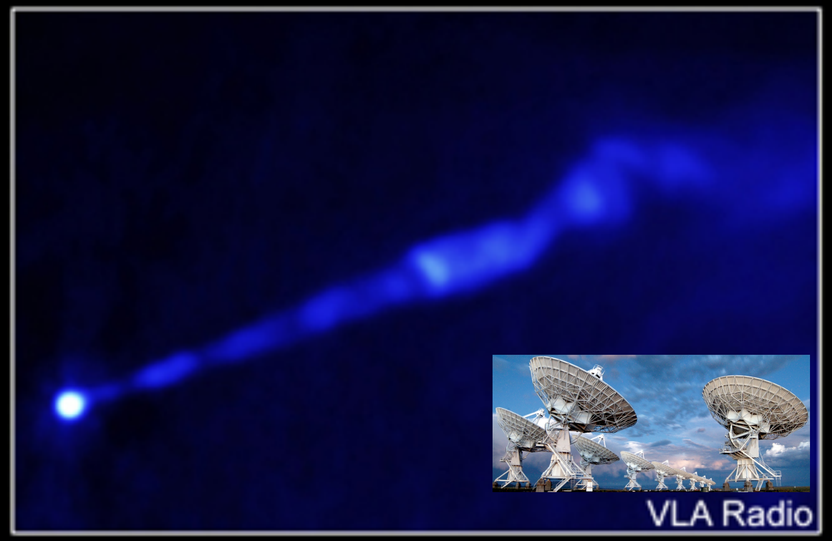


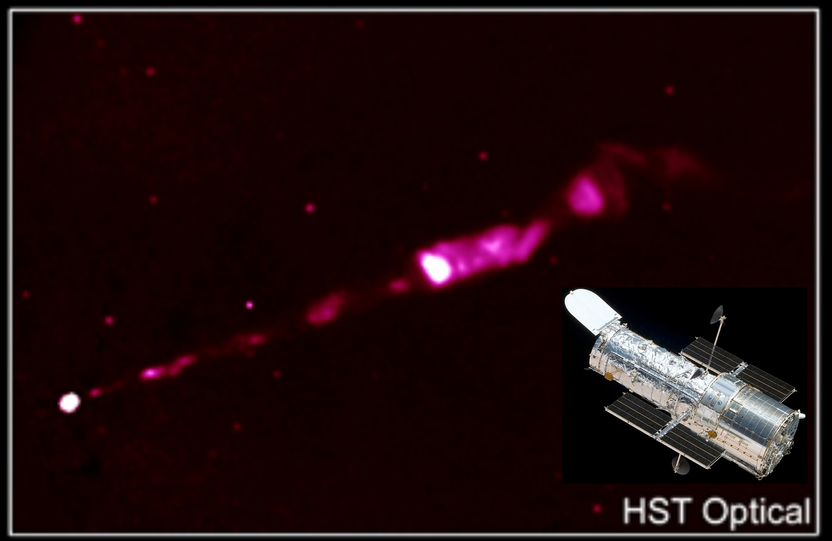


multiwavelength emission
energy dissipation, particle acceleration



radio galaxy
M87





radio galaxy M87

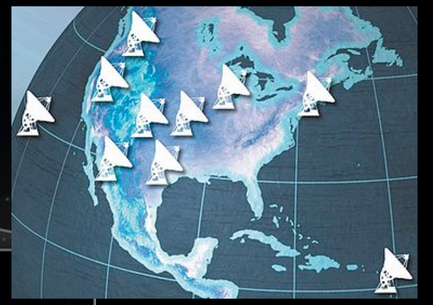
radio→microwaves

Very Large Array

VLA – 1.5 GHz

10 arcseconds

3000 light years



Very Large Baseline Array

VLBA – 43 GHz

0.01 arcseconds

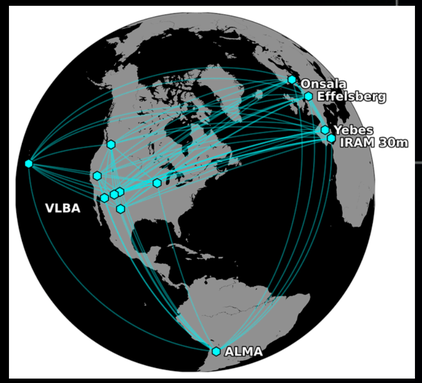
3 light years

GMVA – 86 GHz

0.001 arcseconds

0.3 light years

Global Millimeter VLBI Array

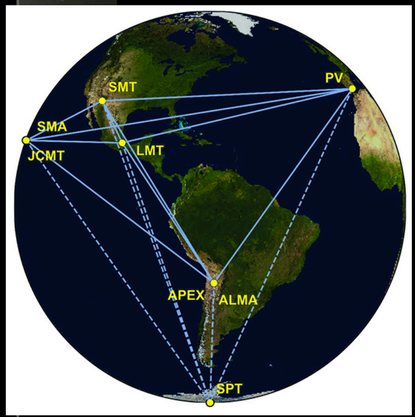


EHT – 230 GHz

0.00001 arcseconds

0.003 light years

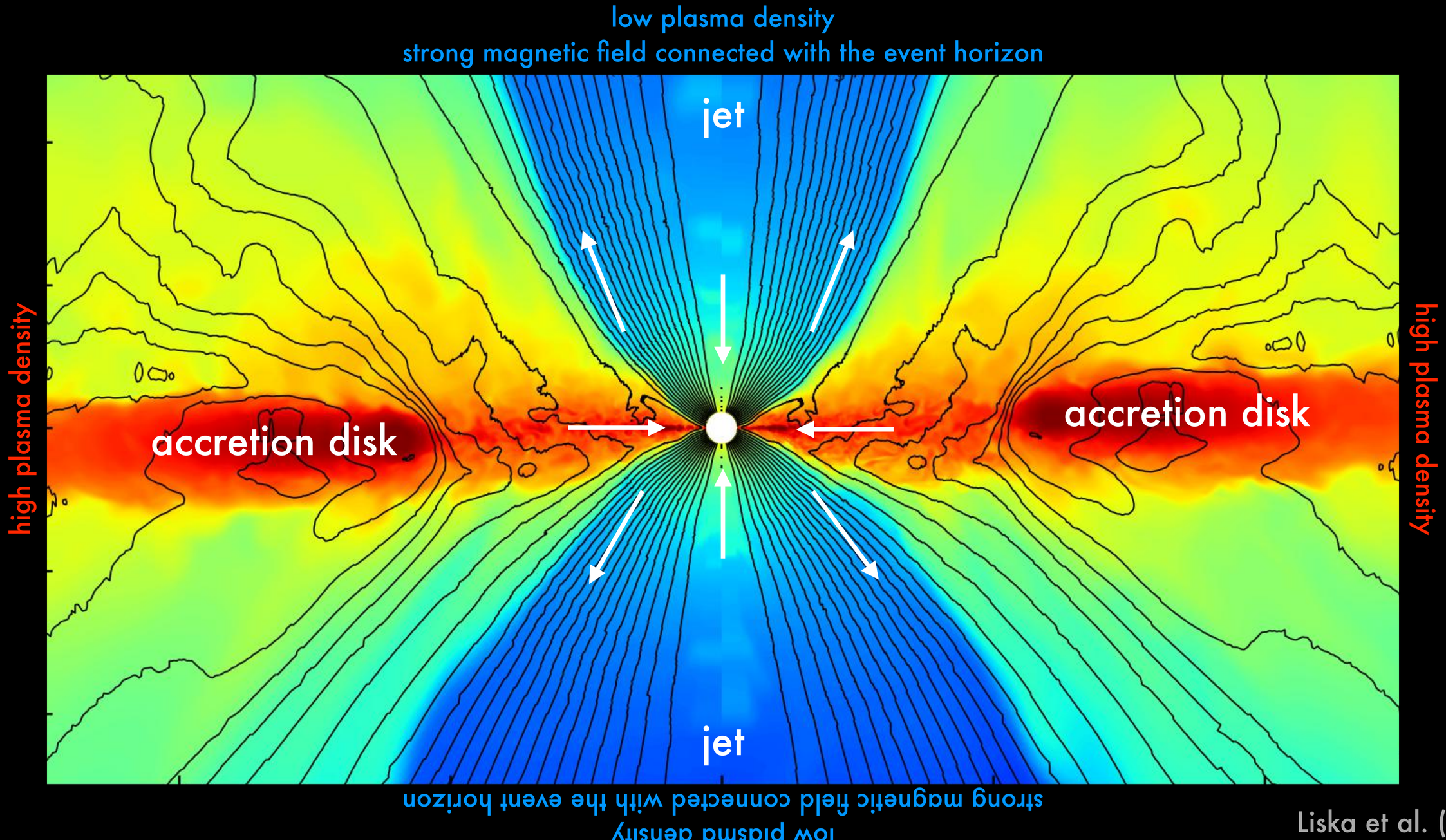
M87*



Event Horizon Telescope

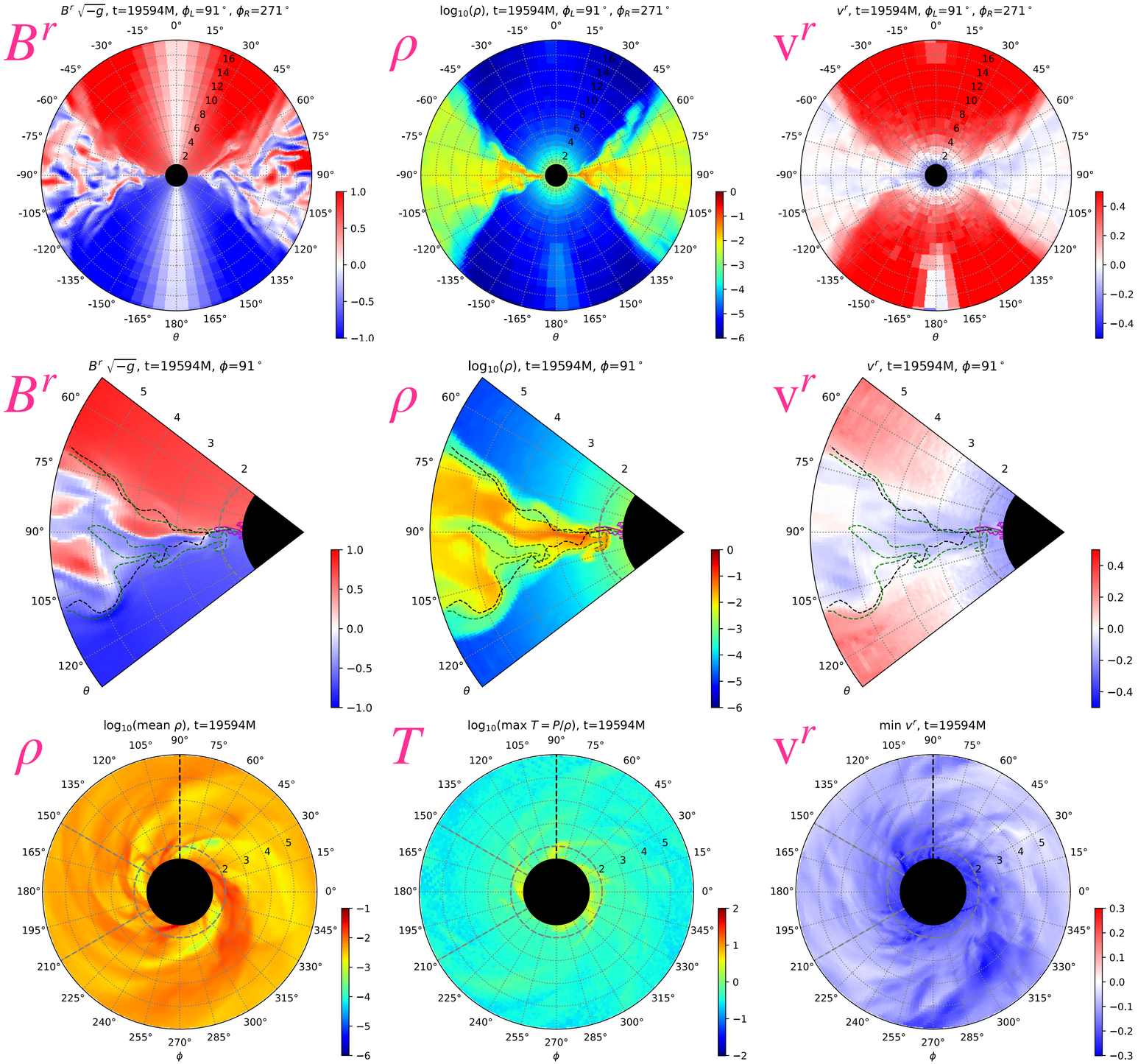
C. Goddi et al. 2019, The Messenger, 177, 25
EHT Collaboration/M. Kornmesser/ESO

magnetized jets: general relativistic magnetohydrodynamics



Liska et al. (2018)

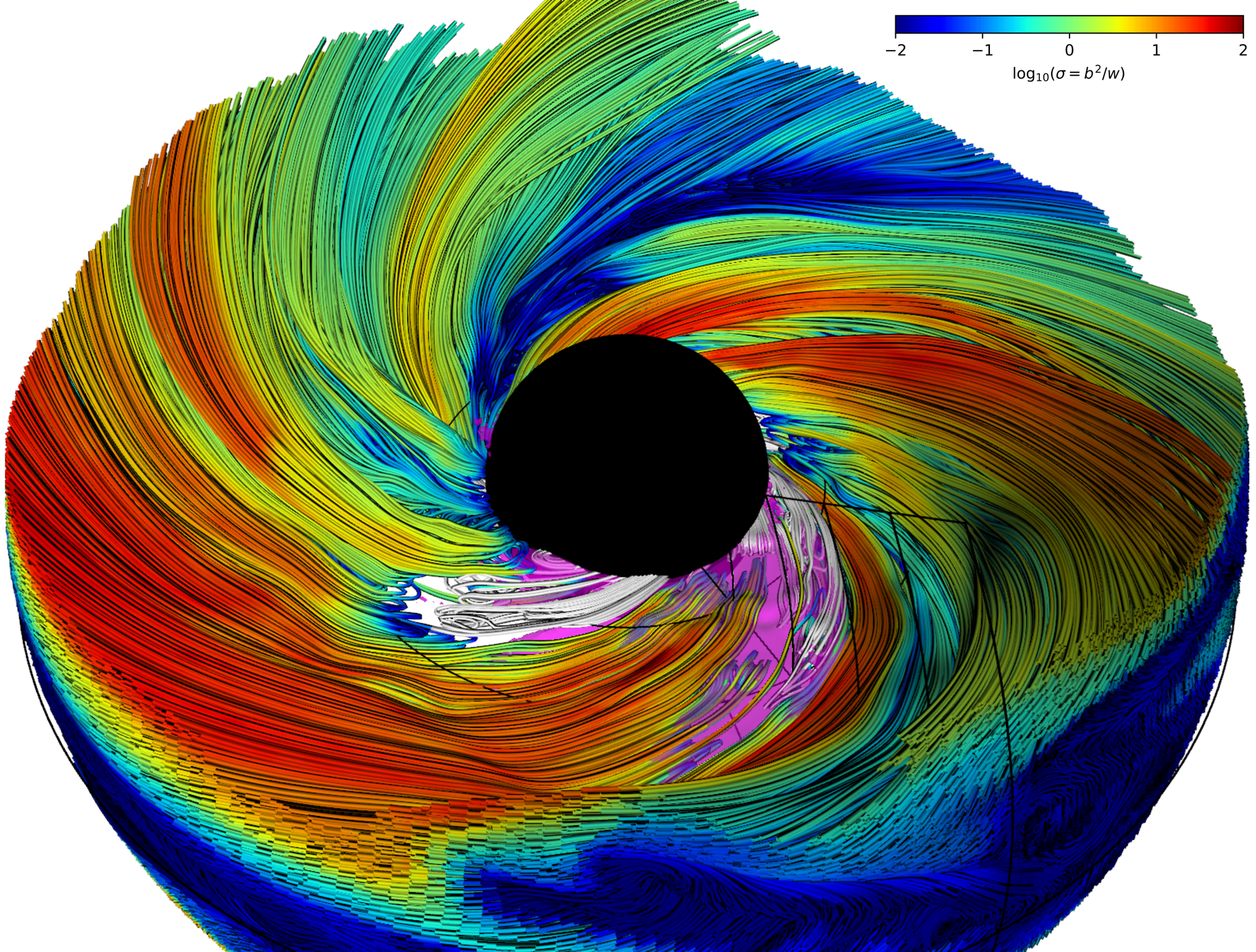
- ideal GRMHD
- Athena++ (HLLE, PPM, vL2)
- Kerr metric ($a = 0.9$)
- Kerr-Schild coordinates $N_r = 288, N_\theta = N_\phi = 256$
- prograde MF76 torus $6M < r < 70M$
- single poloidal field loop



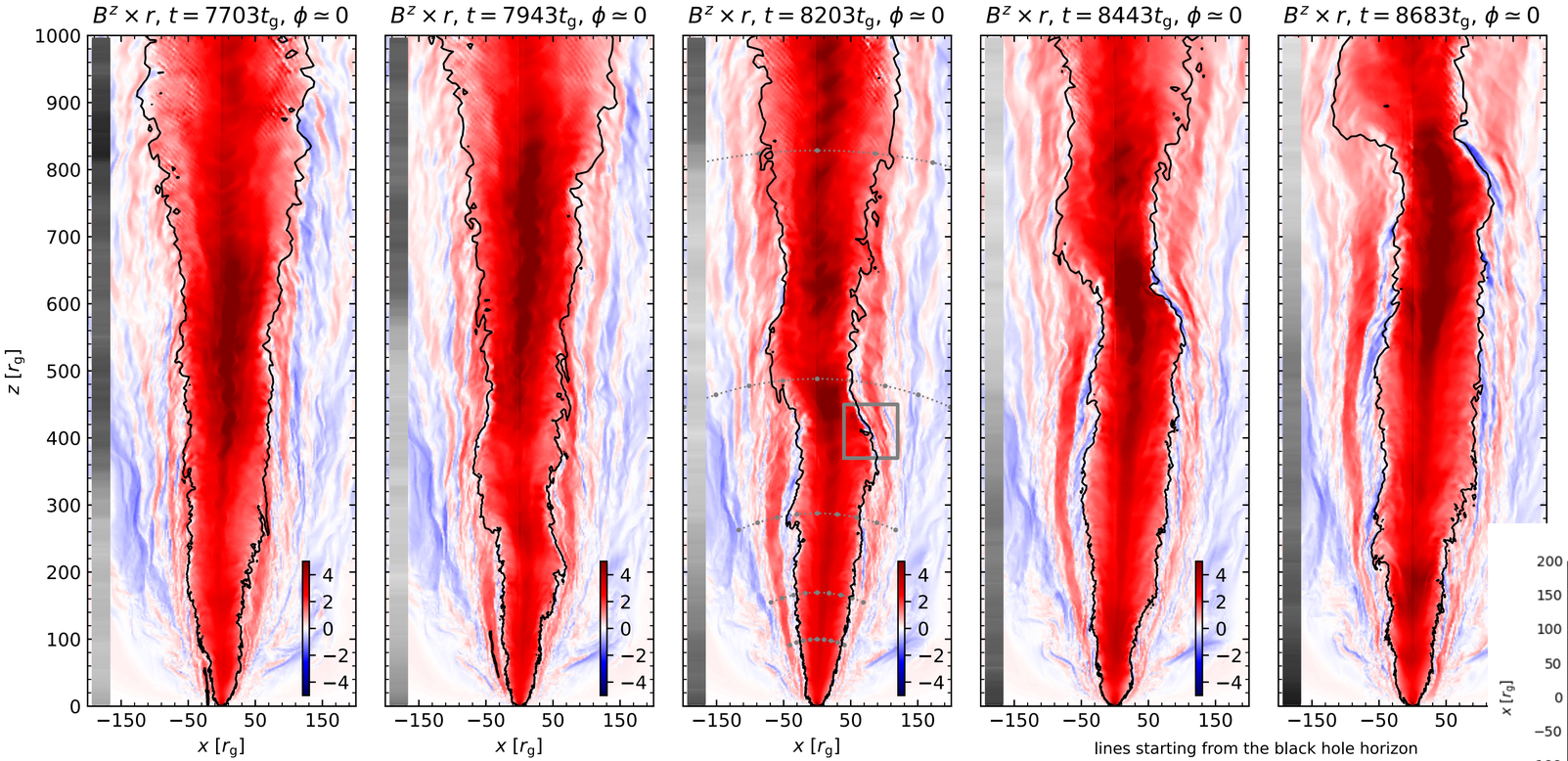
Krzysztof Nalewajko
(Copernicus Astronomical Center, PAS)

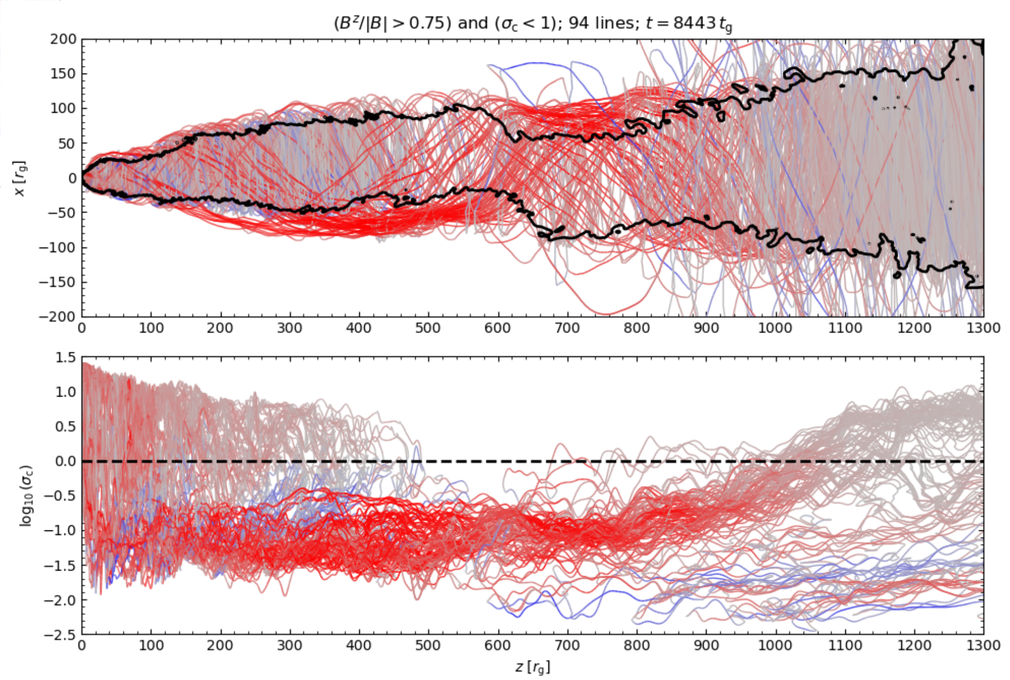
Mateusz Kapusta
(University of Warsaw)

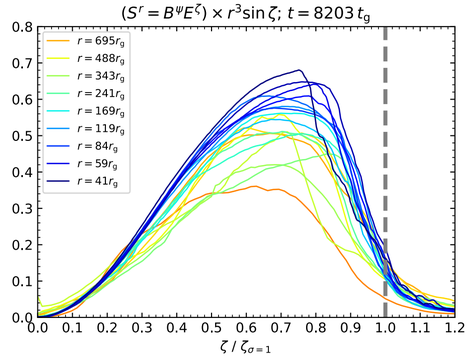
Agnieszka Janiuk
(Center for Theoretical Physics, PAS)

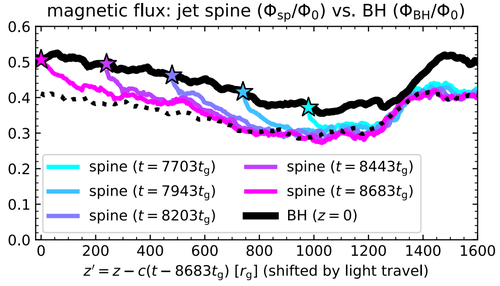


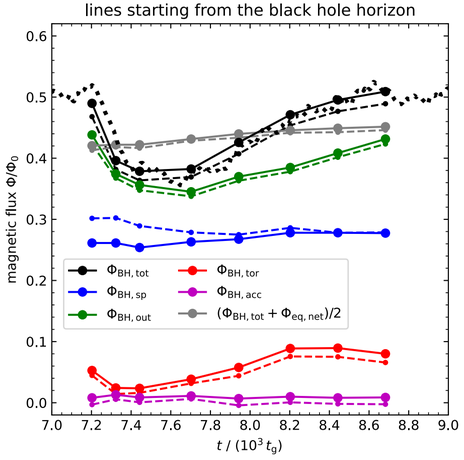
- horizon-disconnected field lines seeded at fixed (θ, ϕ) lattice at $r \simeq 6M$, colored by magnetization $\sigma = b^2/w$
- doubly-connected field loops seeded at $r \lesssim r_{\rm H}$
- relativistic temperature $\log_{10} T > 0.5$

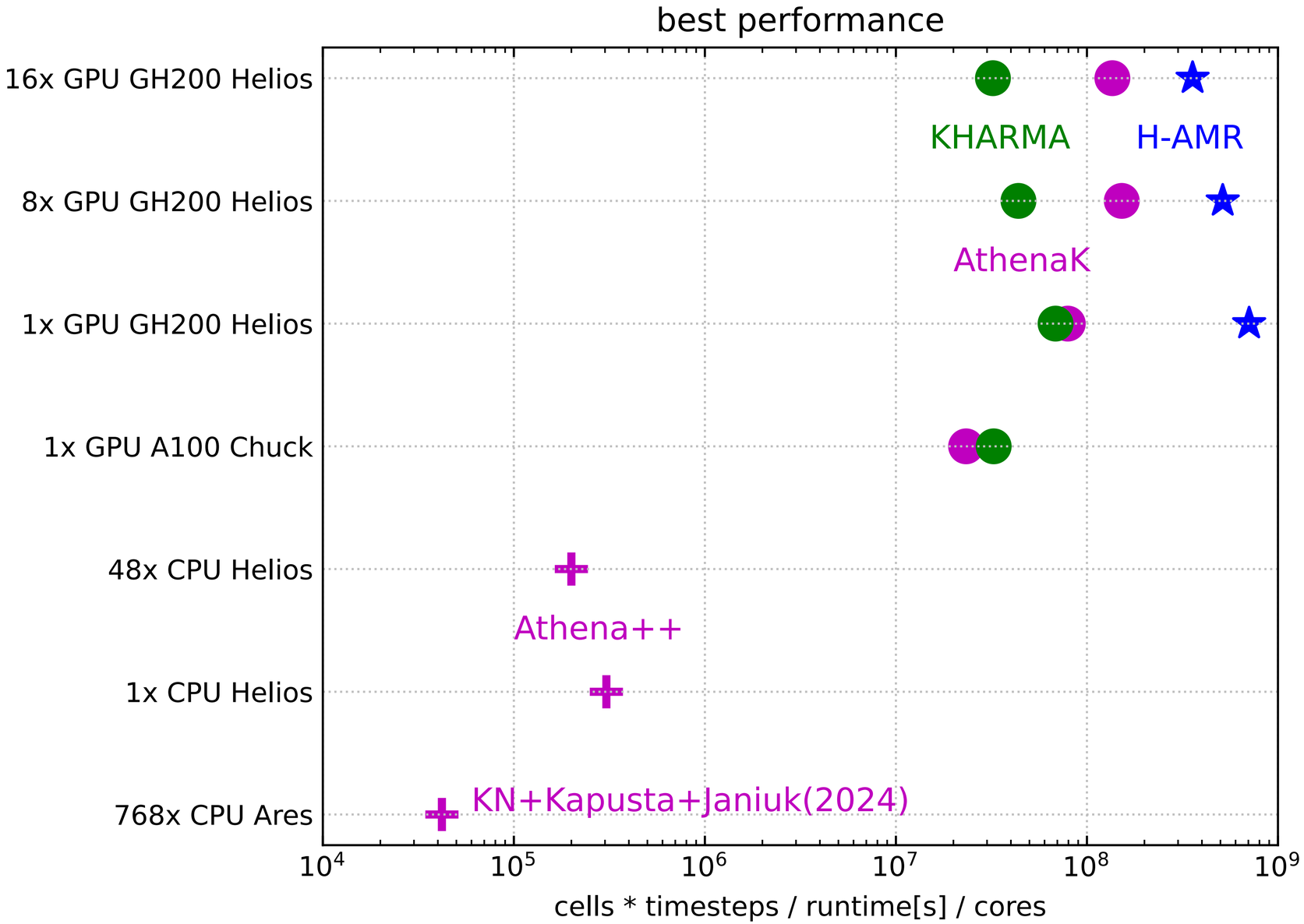

$B^z \times r$, $t = 7703 t_g$, $\phi \simeq 0$
$B^z \times r$, $t = 7943 t_g$, $\phi \simeq 0$
$B^z \times r$, $t = 8203 t_g$, $\phi \simeq 0$
$B^z \times r$, $t = 8443 t_g$, $\phi \simeq 0$
$B^z \times r$, $t = 8683 t_g$, $\phi \simeq 0$
z [r_g]
x [r_g]


$(B^z/|B| > 0.75)$ and $(\sigma_c < 1)$; 94 lines; $t = 8443\, t_g$
x [r_g]
$\log_{10}(\sigma_c)$
z [r_g]


$(S^r = B^\psi E^\zeta) \times r^3 \sin\zeta$; $t = 8203\, t_g$
$r = 695 r_g$
$r = 488 r_g$
$r = 343 r_g$
$r = 241 r_g$
$r = 169 r_g$
$r = 119 r_g$
$r = 84 r_g$
$r = 59 r_g$
$r = 41 r_g$
$\zeta / \zeta_{\sigma=1}$


magnetic flux: jet spine (Φ_{sp}/Φ_0) vs. BH (Φ_{BH}/Φ_0)
spine ($t = 7703 t_g$)
spine ($t = 7943 t_g$)
spine ($t = 8203 t_g$)
spine ($t = 8443 t_g$)
spine ($t = 8683 t_g$)
BH ($z = 0$)
$z' = z - c(t - 8683 t_g)$ [r_g] (shifted by light travel)


lines starting from the black hole horizon
magnetic flux Φ/Φ_0
$\Phi_{BH,tot}$
$\Phi_{BH,sp}$
$\Phi_{BH,out}$
$\Phi_{BH,tor}$
$\Phi_{BH,acc}$
$(\Phi_{BH,tot} + \Phi_{eq,net})/2$
t / ($10^3\, t_g$)


best performance
16x GPU GH200 Helios
8x GPU GH200 Helios
1x GPU GH200 Helios
1x GPU A100 Chuck
48x CPU Helios
1x CPU Helios
768x CPU Ares
KHARMA
H-AMR
AthenaK
Athena++
KN+Kapusta+Janiuk(2024)
10^4
10^5
10^6
10^7
10^8
10^9
cells * timesteps / runtime[s] / cores

SUMMARY

- Relativistic jets are powerful outflows driven by strong magnetic fields in the vicinity of rotating black holes.
- The best studied jet of M87 has been resolved by radio/mm interferometry to the black hole ring image M87* (EHT).
- Global numerical simulations of relativistic jets can be performed by general relativistic magnetohydrodynamics public codes.
- Numerical resources: high performance computers (CPU, GPU) across Poland and Europe; international collaboration.
- Extensive analysis of 3D datasets, e.g., by integrating large samples of magnetic field lines.
- Research group including PhD students Wen Xuan Sia and Jakub Szpila.

knalew@camk.edu.pl