Magnetic Launching of AGN-Jets

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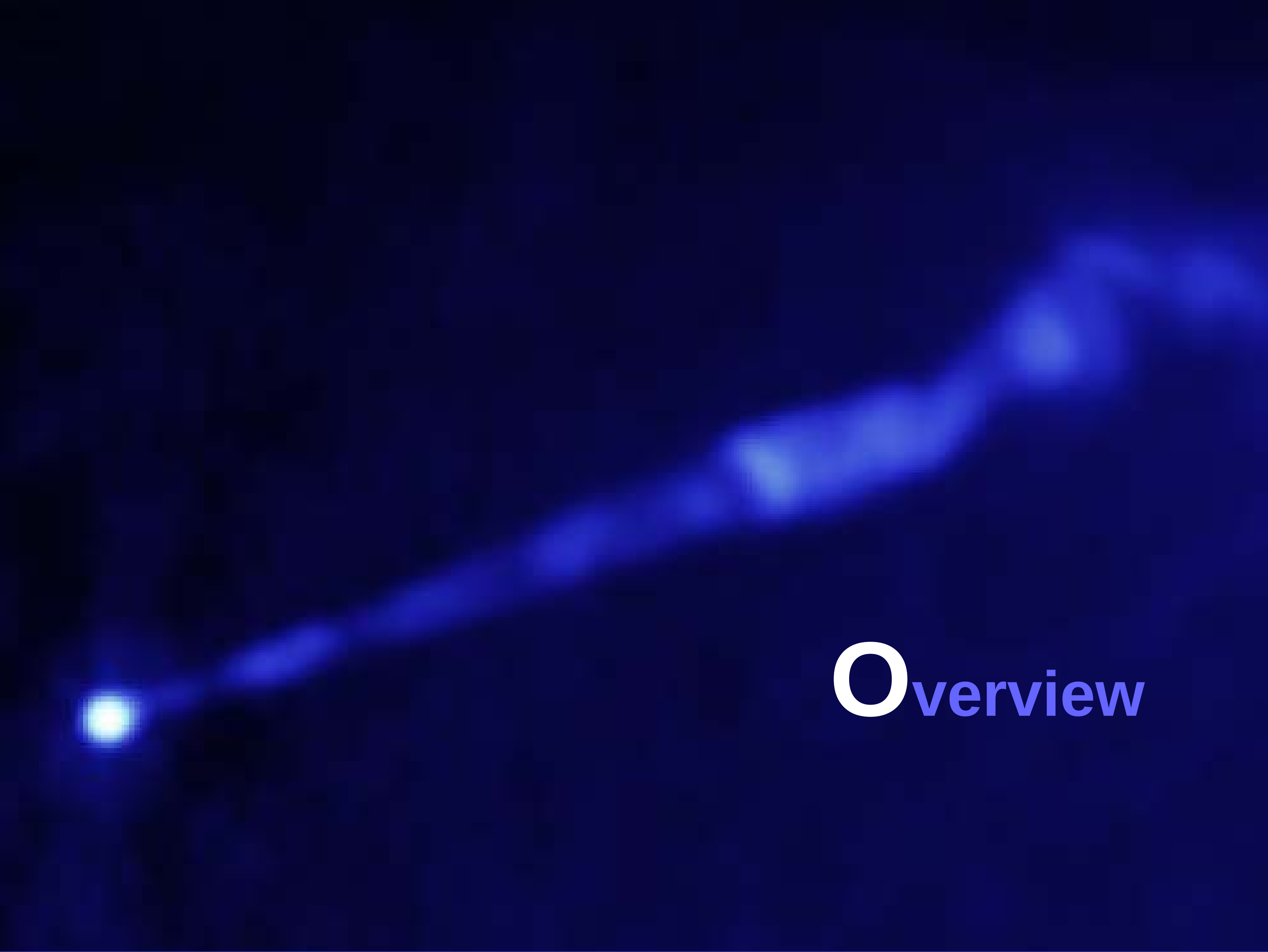
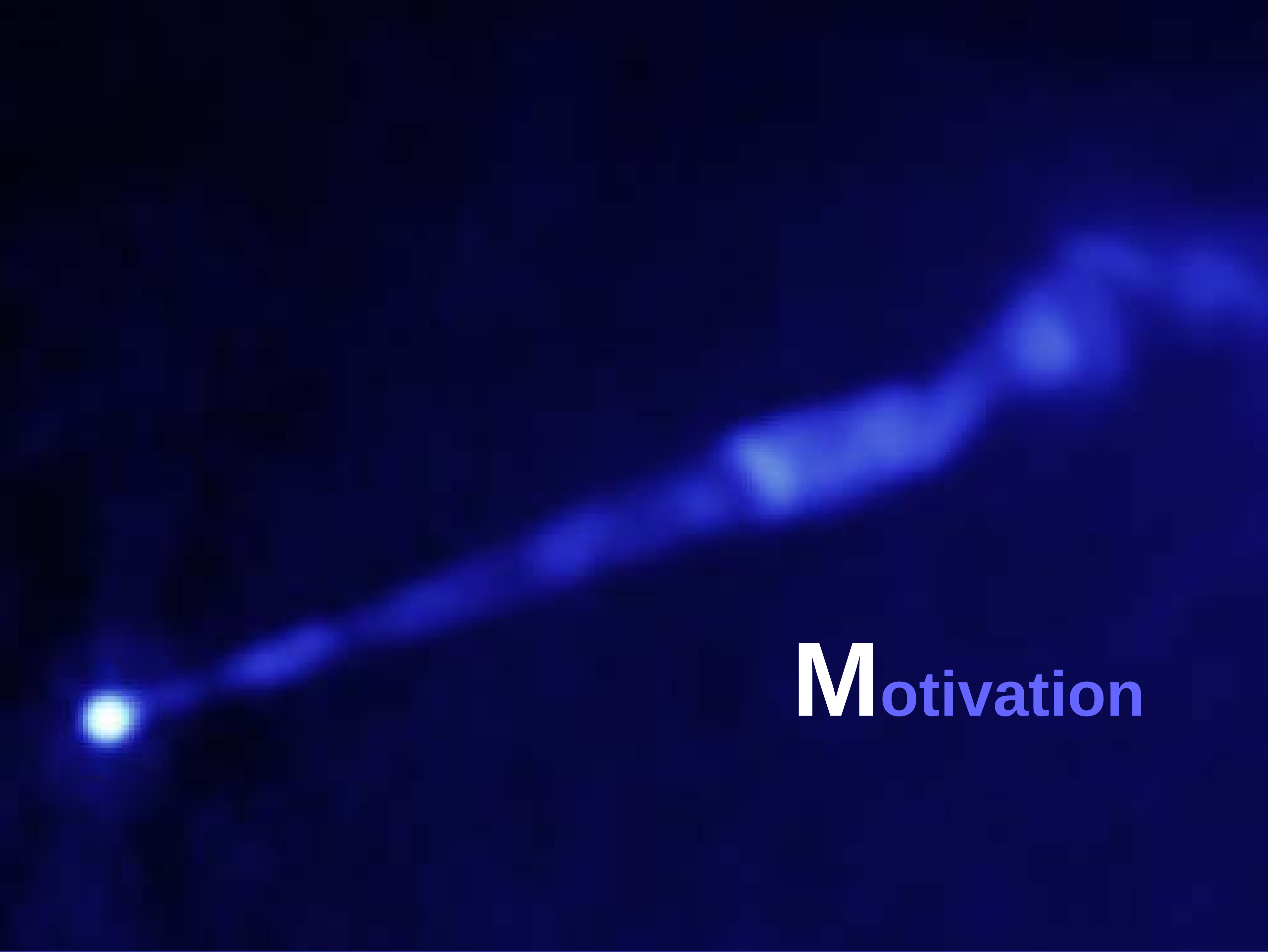
Overview



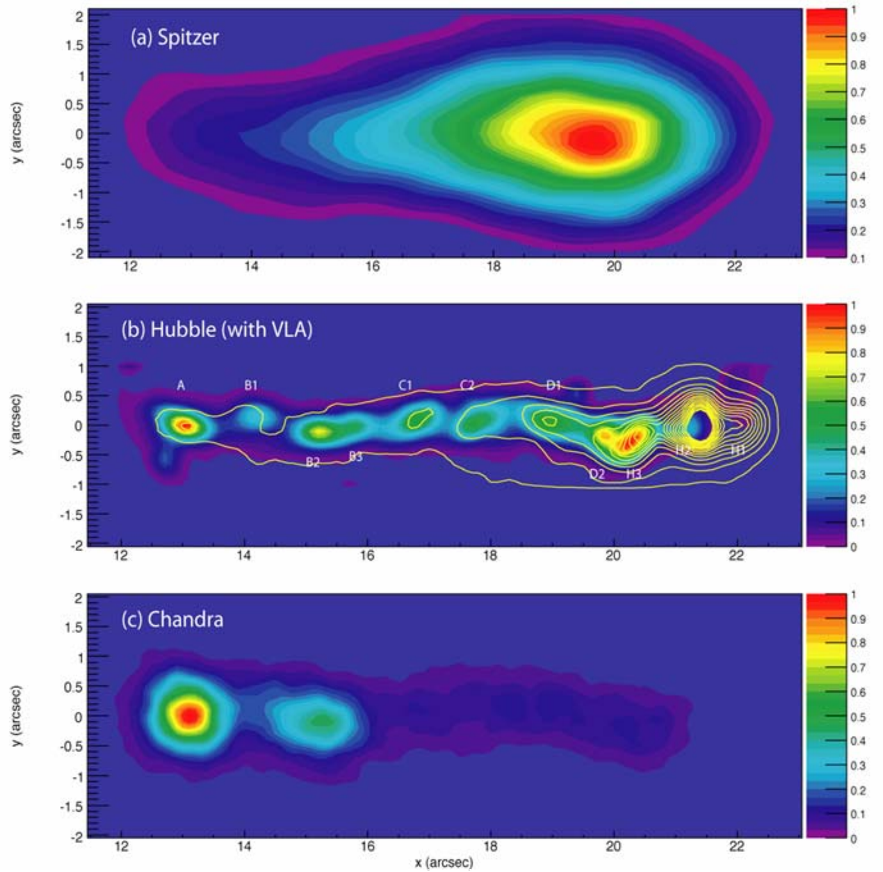
Plan of the talk

- Motivation
- AGN paradigm
- Kerr black holes
- Jet engines
- GRMHD primer
- Status report on GRMHD
- Images & spectra
- Theory meets observations
- Summary & outlook

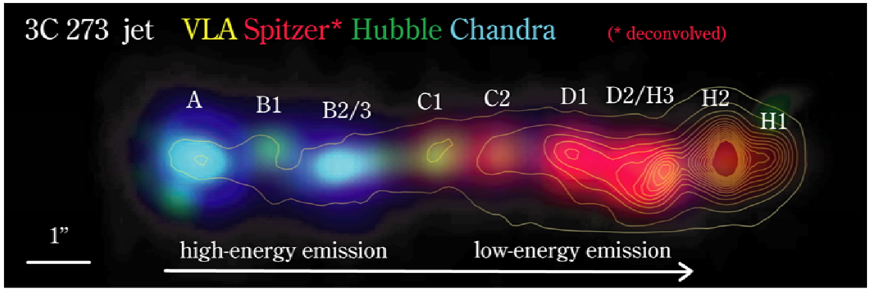


Motivation

Multi-wavelength view on 3C 273 jet



UHE proton source

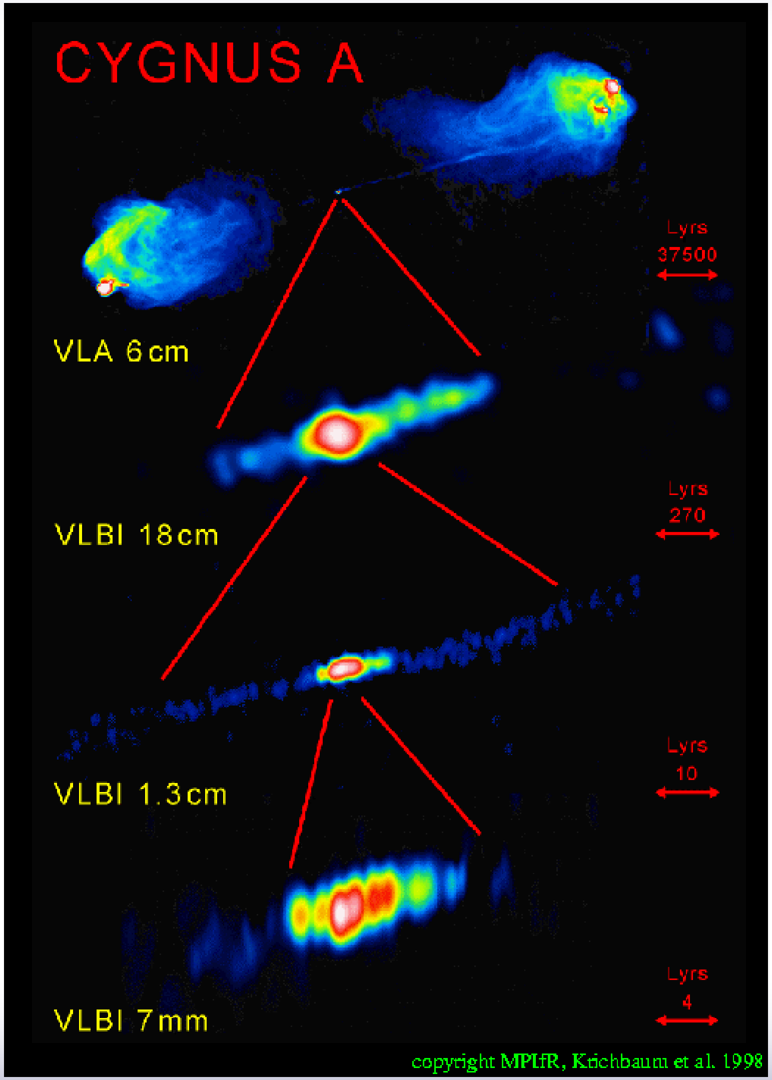


relativistic

$\Gamma \sim 2 \ldots 10$

Uchiyama et al.
ApJ 2006

Zooming into AGN with VLBI

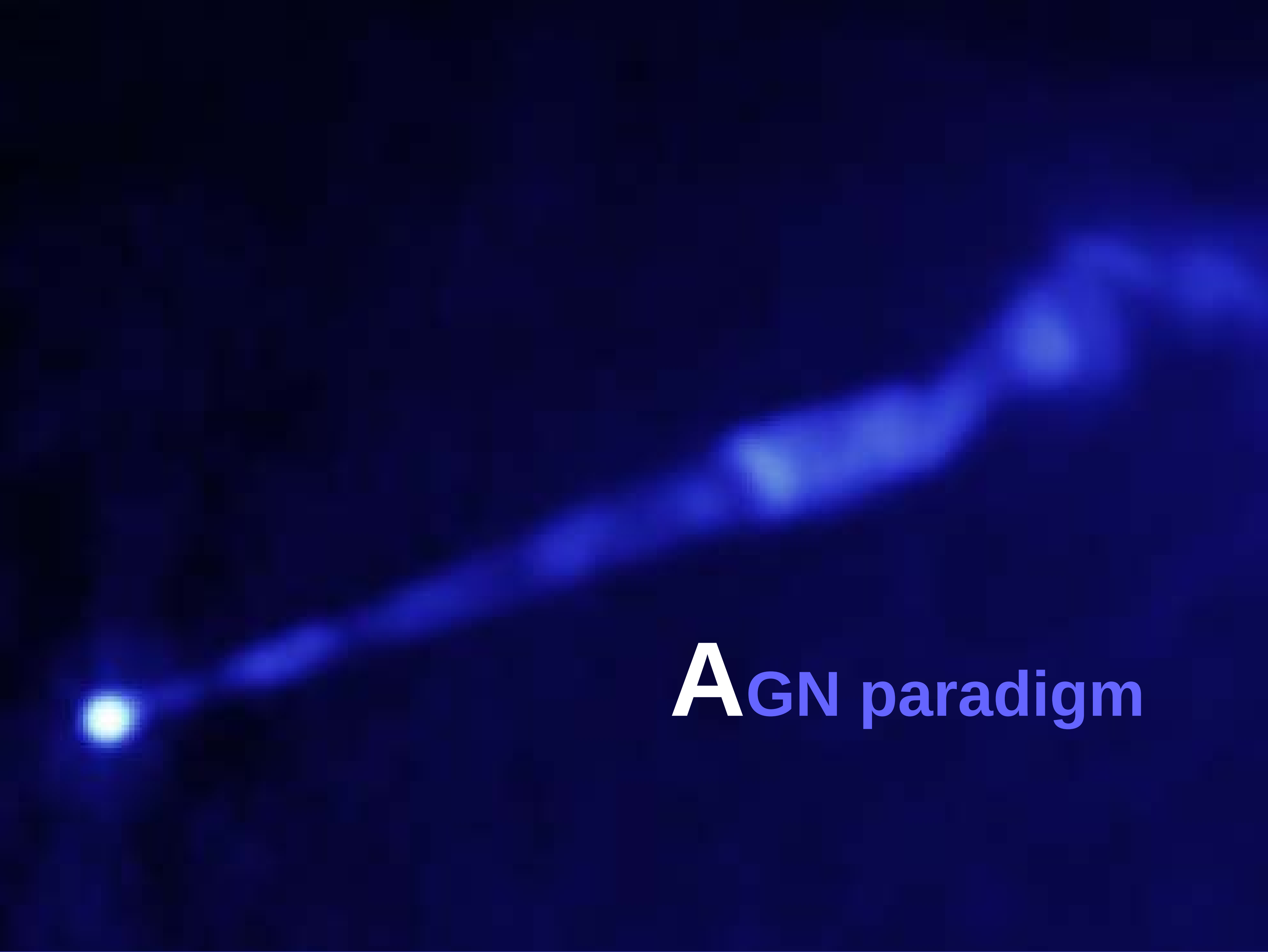


mm-VLBI:

- Jet base
- Jet engine
- BH imaging

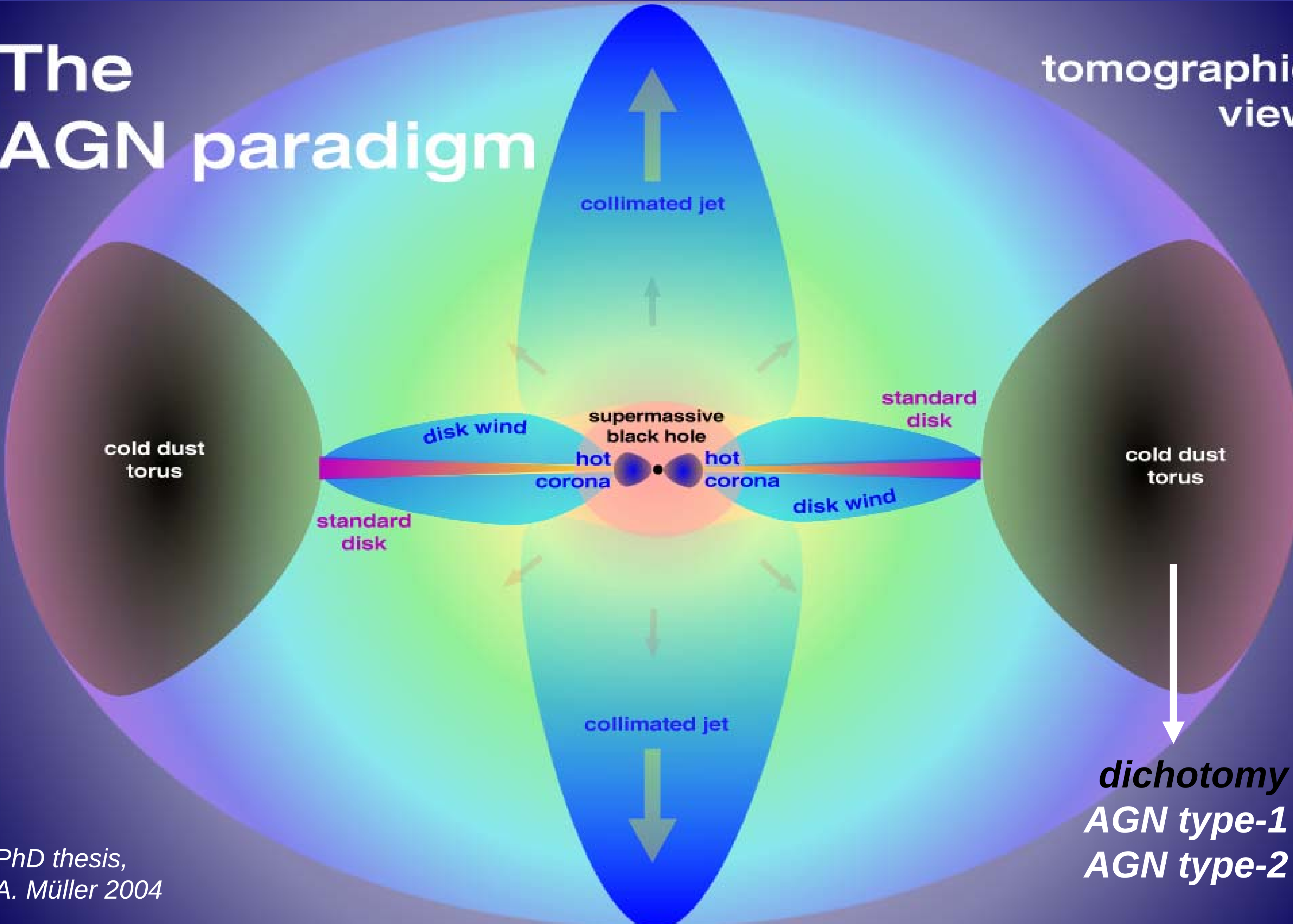
Krichbaum et al. 1998

AGN paradigm



The AGN paradigm

tomographic view

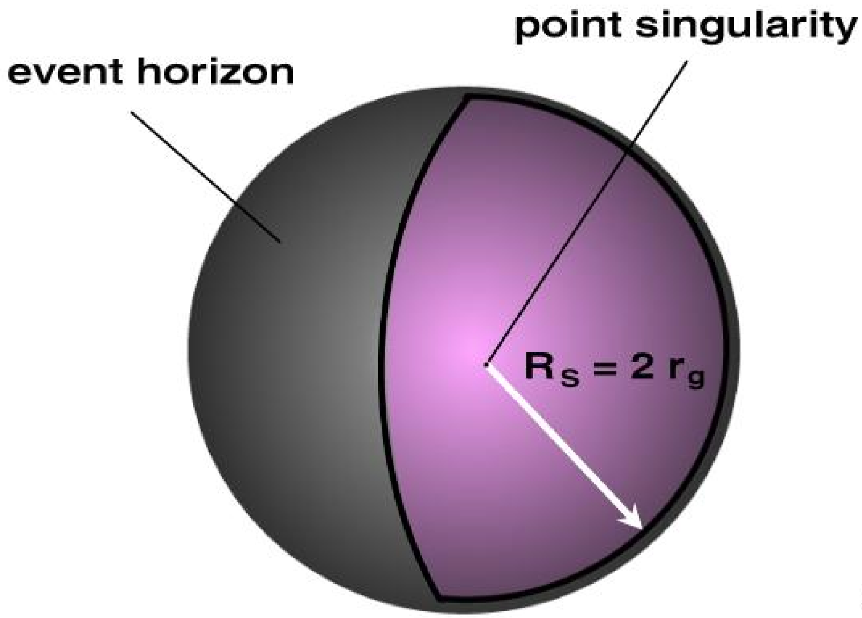


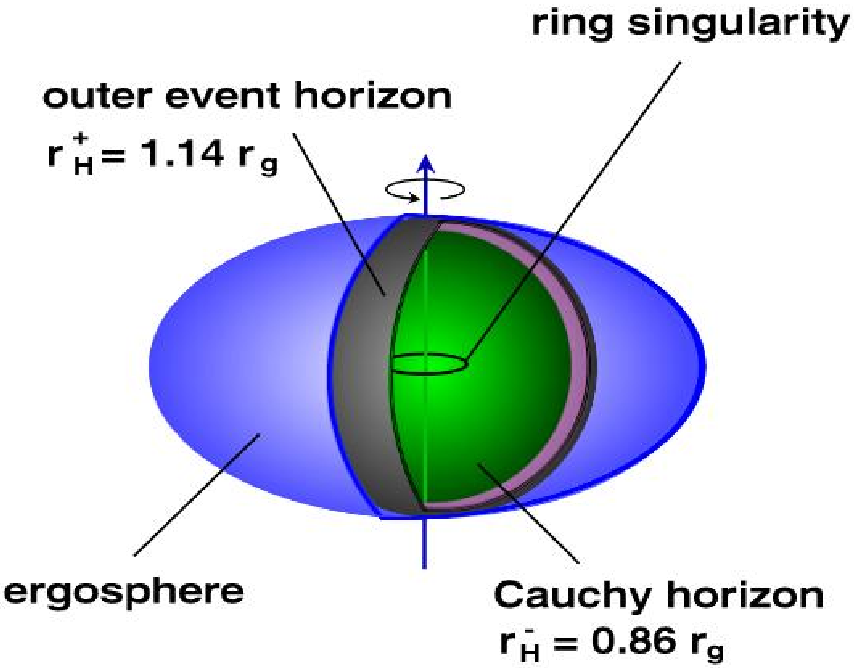
PhD thesis,
A. Müller 2004

dichotomy
AGN type-1
AGN type-2

Kerr black holes

Static vs. rotating black holes





Schwarzschild

1916

Kerr

1963

Kerr metric (*Boyer-Lindquist form*)

$$ds^2 = -\alpha^2 dt^2 + \tilde{\omega}^2 (d\phi - \omega dt)^2 + \rho^2/\Delta \; dr^2 + \rho^2 d\theta^2$$

with functions

$$\alpha = \frac{\rho\sqrt{\Delta}}{\Sigma},$$ redshift, lapse function

$$\Delta = r^2 - 2Mr + a^2,$$

$$\rho^2 = r^2 + a^2 \cos^2\theta,$$

$$\Sigma^2 = (r^2 + a^2)^2 - a^2 \Delta \sin^2\theta,$$

$$\omega = \frac{2aMr}{\Sigma^2},$$ frame-dragging frequency *(steep gradient)*

$$\tilde{\omega} = \frac{\Sigma}{\rho} \sin\theta.$$ cylindrical radius

BH mass *M*,
BH spin *a*

(geometrized units G = c = 1)

Kerr metric (*Kerr-Schild form*)

$$ds^2 = -(1-Z)\,d\tilde{t}^2 - 2Za\sin^2\theta\,d\tilde{t}\,d\tilde{\phi} + 2Z\,d\tilde{t}\,dr + \left(\frac{\Sigma\sin\theta}{\rho}\right)^2 d\tilde{\phi}^2$$
$$-2a\,(1+Z)\sin^2\theta\,d\tilde{\phi}\,dr + (1+Z)\,dr^2 + \rho^2\,d\theta^2$$

with function $Z = 2Mr/\rho^2$ *(e.g. Komissarov 2004)*

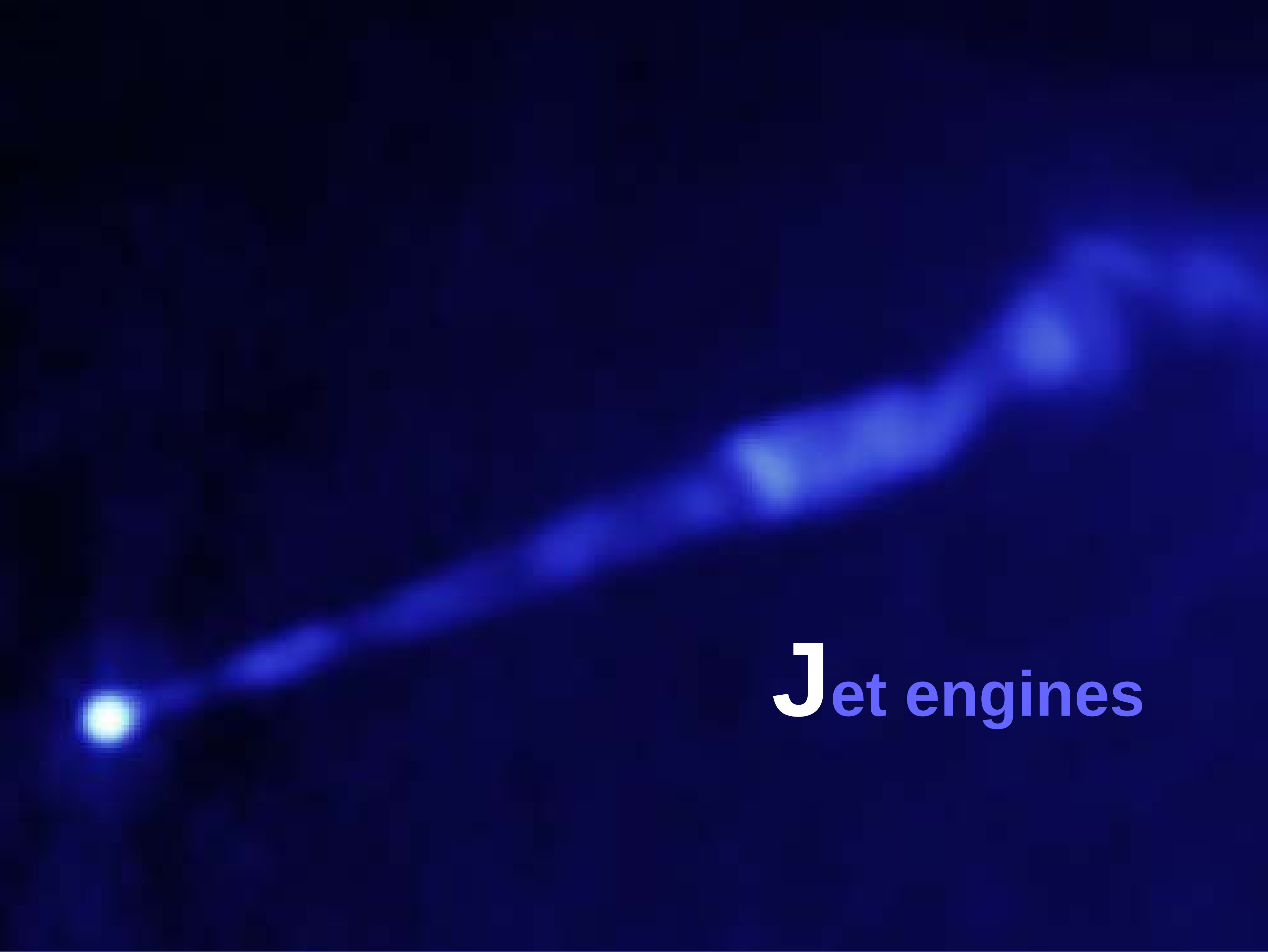
Coordinate singularity at event horizon removed!

Three non-vanishing cross-terms

Very convenient to set **inner boundary** condition inside horizon.

This is a complexity but **not a serious** numerical problem.

Jet engines



Blandford-Znajek process (1977)

- accretion flow feeds rotating BH
- $T^{\mu\nu} = T^{\mu\nu}_{EM}$ only (force-free model *without* fluid matter)
- BH interacts with magnetic field lines
- large fields: e^+e^- pairs, leptonic plasma
- extraction of BH‘s rotational energy
- acceleration of leptons

  $v_{outflow} \sim c$
- radial distance $r < 2\ r_g$
- mechanism works only **with Kerr BH**

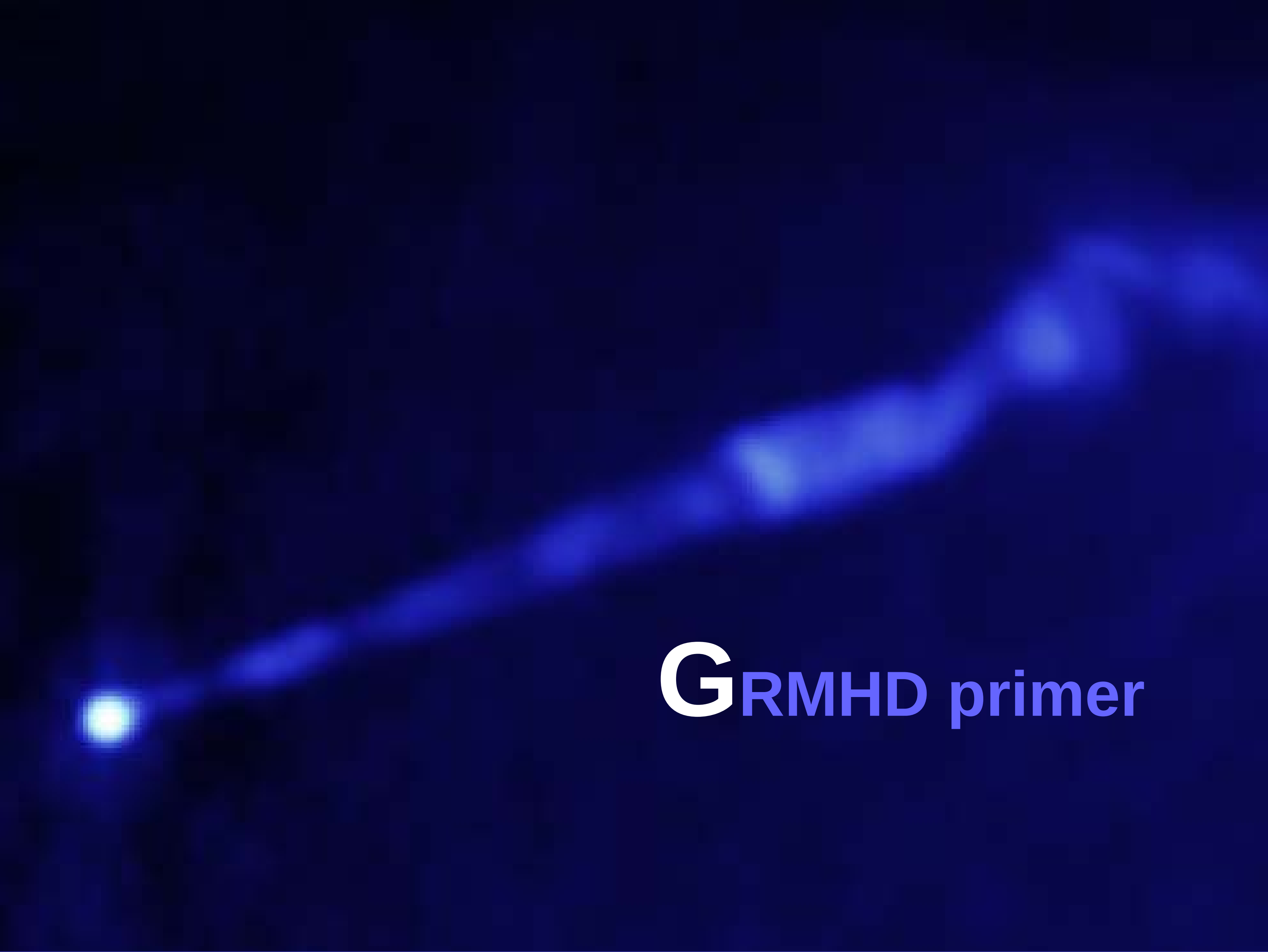
Blandford-Payne scenario (1982)

- magnetised accretion disk
- plasma extraction along magnetic flux tubes
- analogue: solar MHD (Sun spots etc.)
- magnetic pressure and centrifugally driven outflows (wind)

  $v_{wind} \sim v_{Kep} \sim r^{-1/2}$

  („magnetic sling shot mechanism“)
- radial distances few to several 100 r_g
- mechanism works also **without BH**

GRMHD primer



HowTo do GRMHD - on one slide!

- energy stress tensor: $T^{\mu\nu} = T^{\mu\nu}_{\text{perfect fluid}} + T^{\mu\nu}_{\text{EM}}$
- specify metric, e.g. Kerr geometry (*background metric*)
- metric: Boyer-Lindquist vs. Kerr-Schild coordinates
- numerical relativity: apply ADM formalism (3+1 split)
- solver: non-conservative vs. conservative schemes
- run: specify initial and boundary conditions
- solve coupled Einstein-Maxwell system of MHD equations

- many sophisticated technical details involved…

Status report on GRMHD

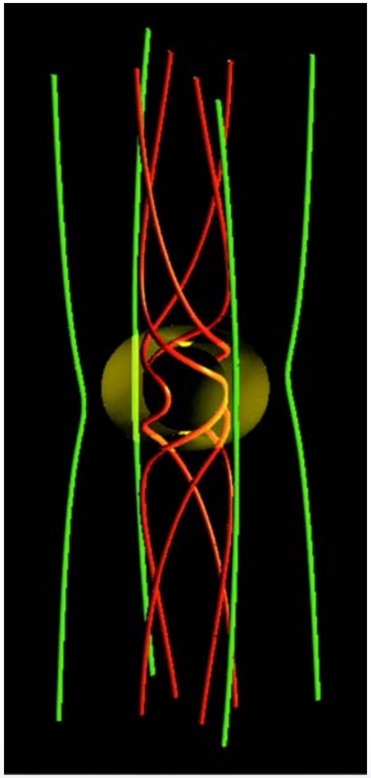
GRMHD codes

▪ Wilson, J. R., proc. 1975	fixed metric, acc.+stellar collapse
▪ Yokosawa, M., PASJ 1993	fixed metric, KBH accretion
▪ Banyuls et al., ApJ 1997	fixed metric, SBH accretion
▪ Koide et al., ApJ 1999	fixed metric, KBH acc.+jets
▪ De Villiers & Hawley, ApJ 2002	fixed metric, KBH acc.+jets
▪ Gammie et al., ApJ 2003	fixed metric, KBH acc.+jets
▪ Komissarov, MNRAS 2004	fixed metric, BZ effect
▪ Shibata & Sekiguchi, PRD 2005	fixed metric, KBH acc.+jets
▪ Duez et al., PRD 2005	dynamical metric, GRMHD+GW
▪ Anninos et al., ApJ 2005	fixed metric, KBH acc.+jets
▪ Anton et al., ApJ 2006	fixed metric, KBH accretion
▪ McKinney, MNRAS 2006	fixed metric, KBH acc.+jets
▪ Mizuno et al., subm. 2006	fixed metric, KBH acc.+jets, GRBs, GRPIC

Frame-dragging & MHD-Penrose process

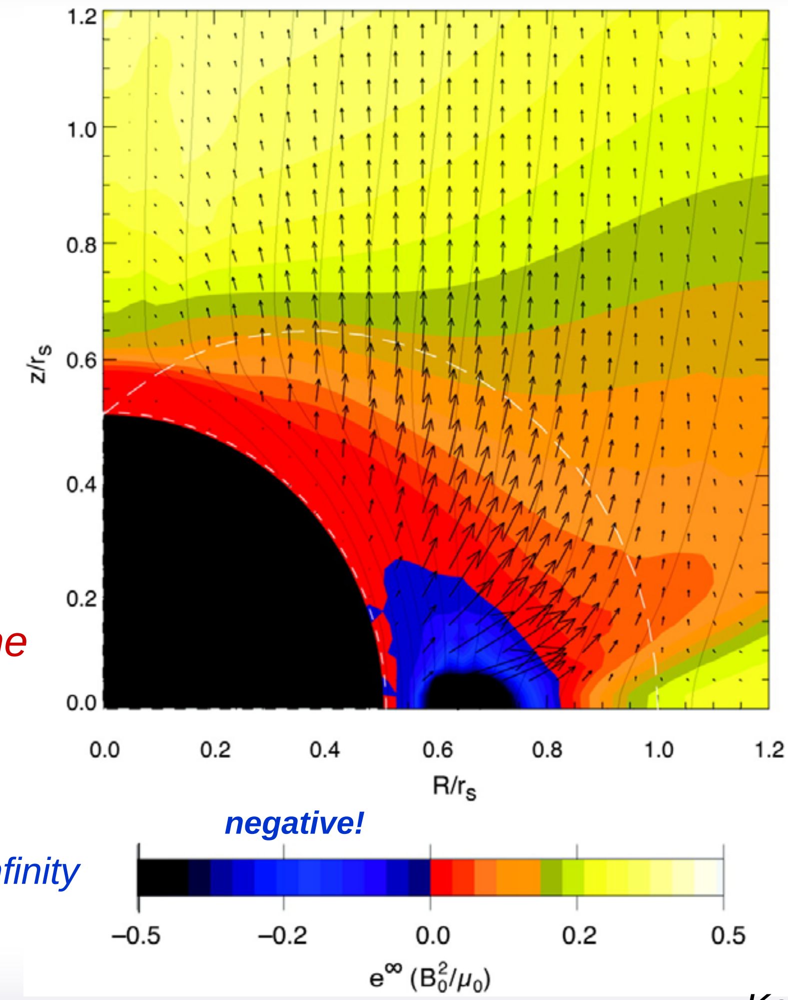
$$\Omega(r_H) = \omega(r_H) = \frac{a}{2r_H} \equiv \Omega_H$$

(cf. gravitomagnetism)



arrows: *EM energy flux density*

main result:
outward directed torsional Alfvén wave is driven by rotating space-time

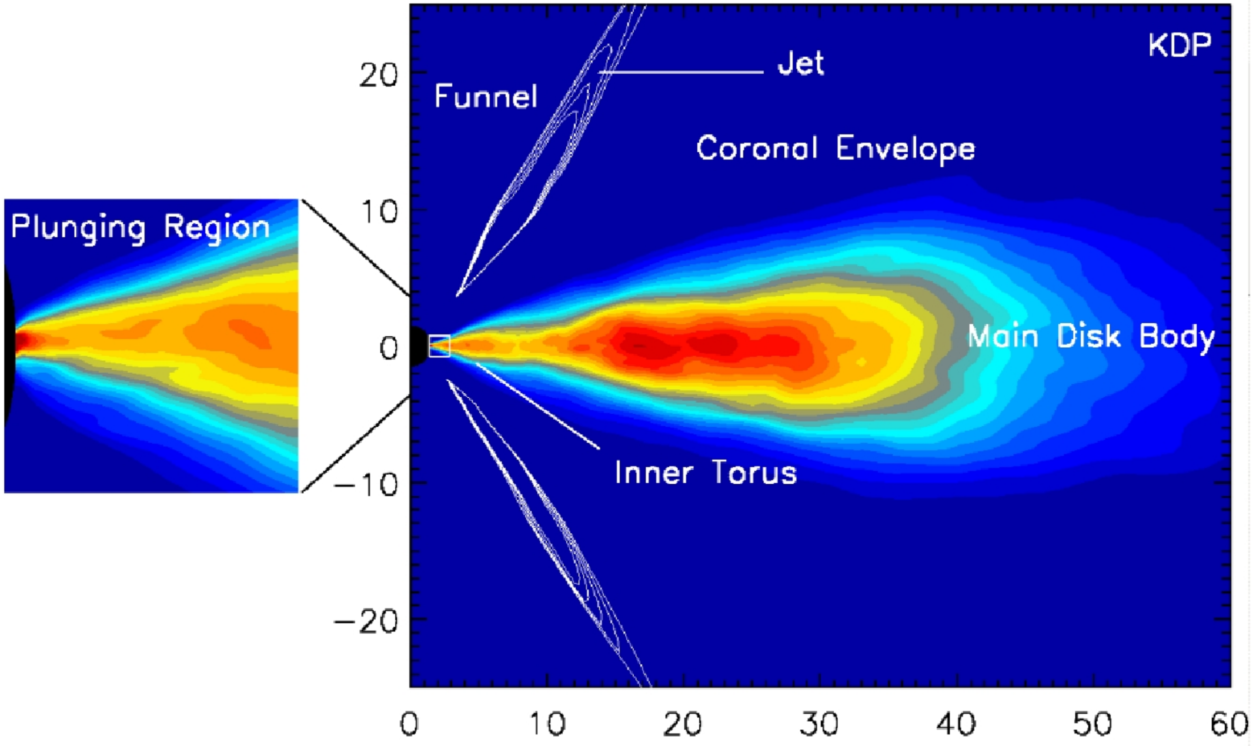


energy density at infinity

Koide et al. 2002

MRI-induced torus decay and funnel-jet

azimuthally-averaged density, time-averaged after 10th orbit



parameters:

$a = 0.9$ M
$\beta = p_{gas}/p_{mag} = 200$

$r_{in} = 15\ r_g$
$r_{pmax} = 25\ r_g$

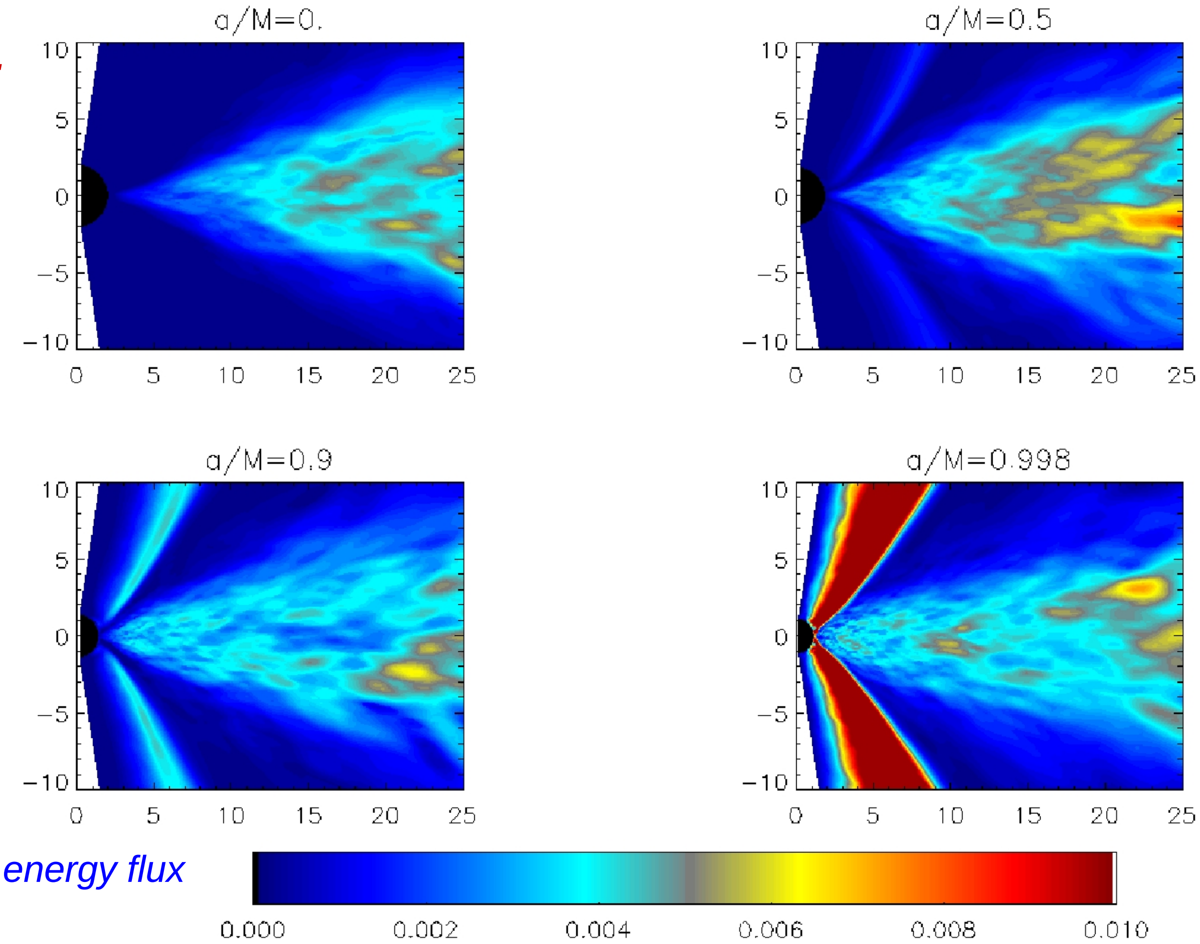
Thick disk supports MRI growth!

De Villiers et al. 2003

*(remark: flow bridges **smoothly and continuously** ISCO)*

Magneto-rotationally driven outflows

non-rotating: no EM flux

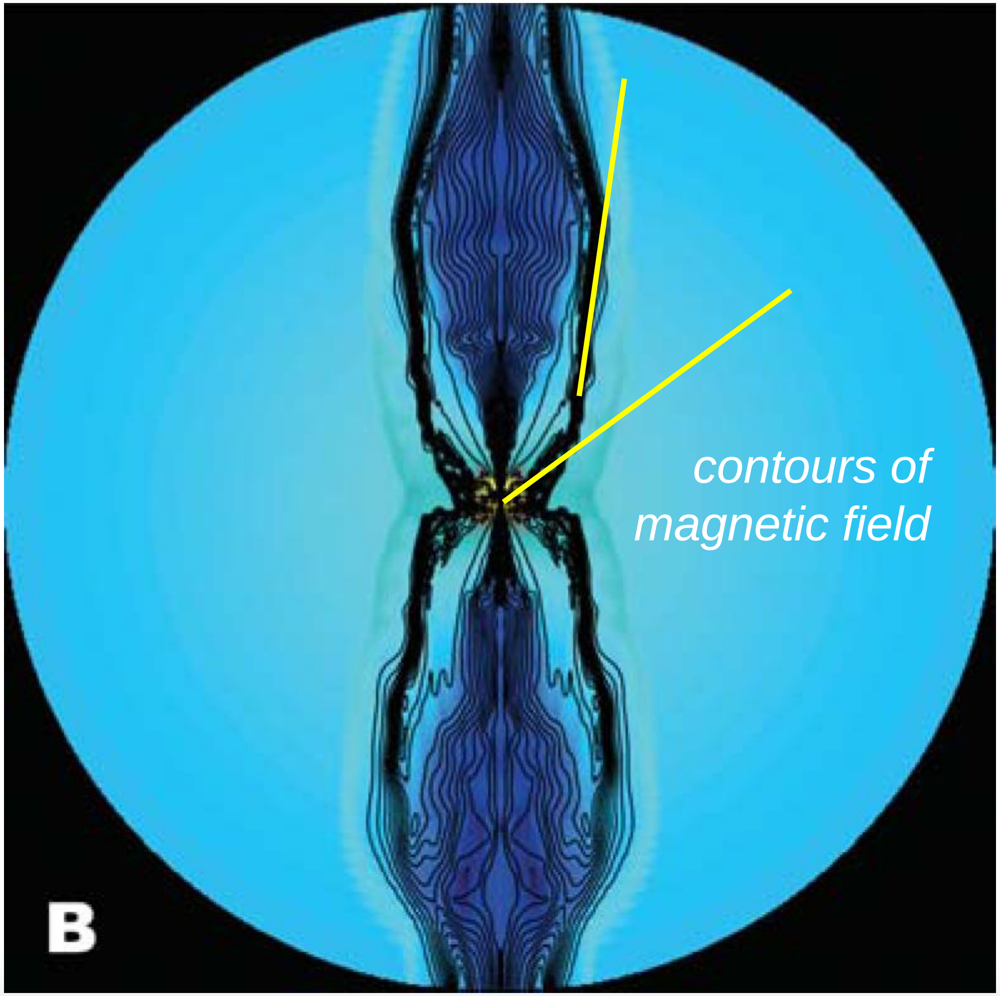


rapidly rotating: Kerr BH drives strong EM flux

electromagnetic energy flux

Krolik et al. 2004

Jet collimation



$10^4\ r_g$

initial torus configuration,
turbulent decay by MRI

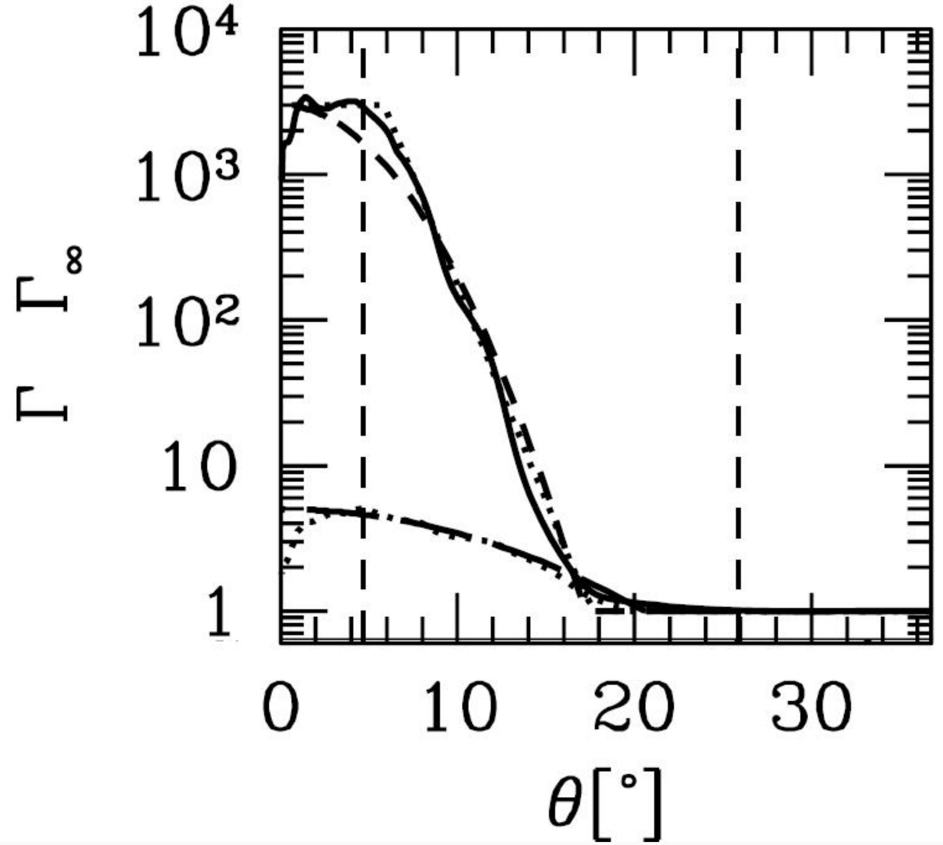
Jet morphologies:
paraboloidal core,
conical out part ($r > 10^3\ r_g$)

half-opening angle collimates from θ_j **~ 60°** *near BH to* θ_j **~ 5°** *at several 100* r_g *distance*

(consistent e.g. with M87)

McKinney 2006

New: GRMHD produces high Γ



Γ Lorentz factor with respect to observer at infinity

Γ_{inf} maximum terminal Lorentz factor

θ cross-section at 5000 r_g:
fast core („spine")
BZ flux ~ $\sin^2\theta$

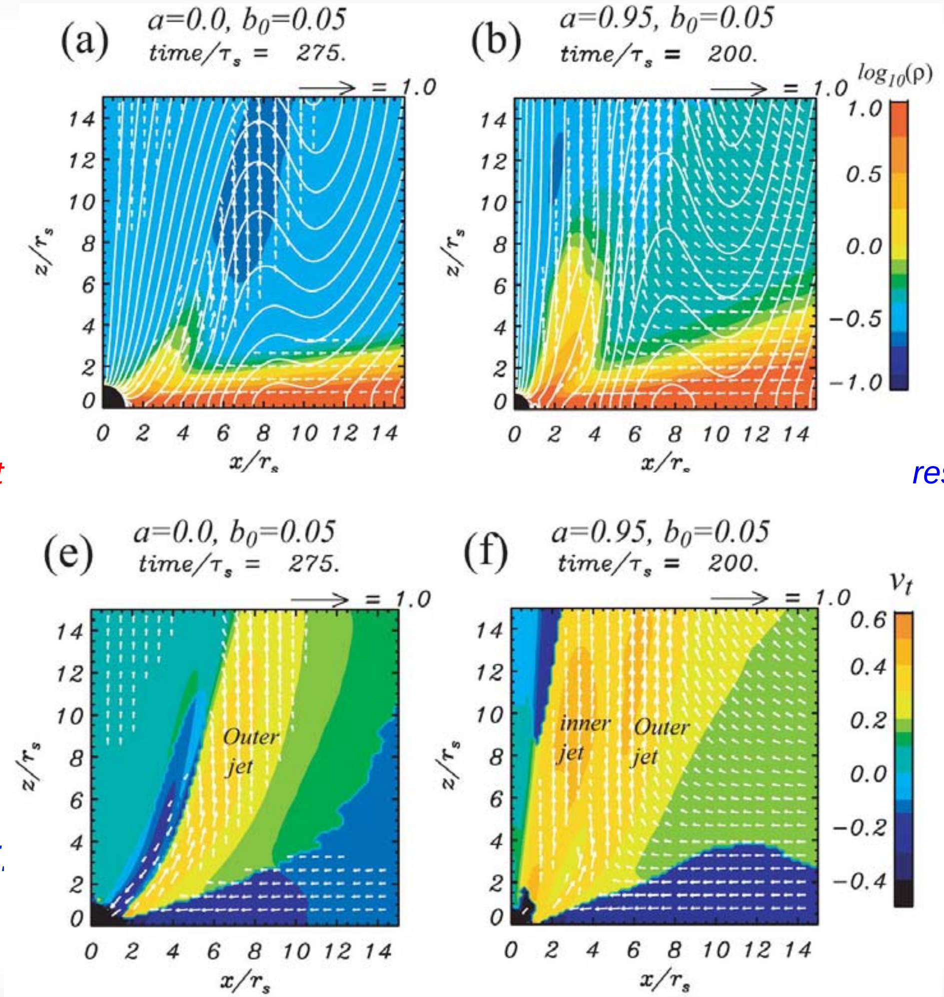
(dashed: Gaussian fits
dotted: exponential fits;
*often **Gaussian Jet structures**)*

McKinney 2006

Two jets from thin Keplerian disk

White contours:
poloidal vector potential

arrows:
poloidal velocities



density

*results after **7 orbits** at Schw ISCO*

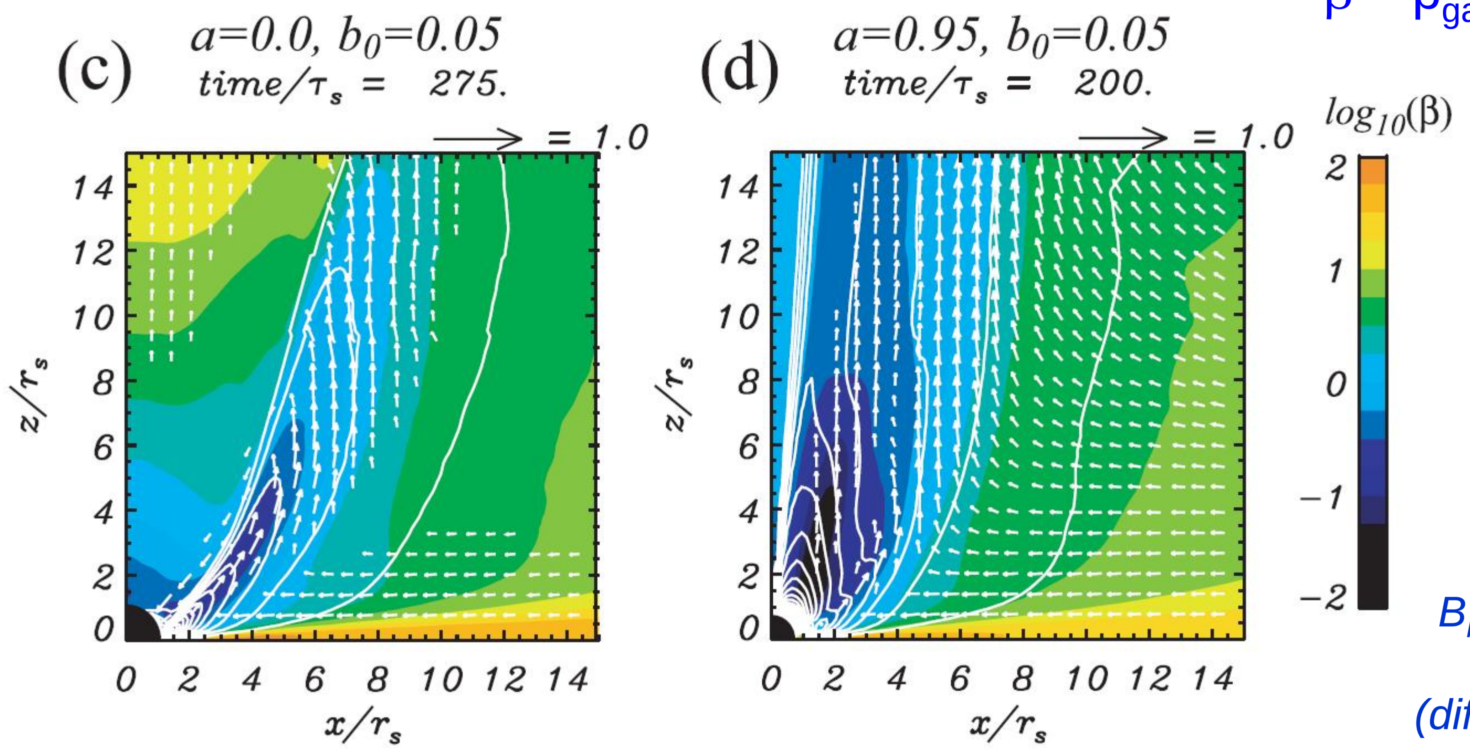
*results after **5 orbits** at Schw ISCO*

***New feature:** inner more collimated, denser and faster jet.*

total velocity

Mizuno et al. 2006, astro-ph/0609344

Two jets from thin Keplerian disk



$\beta = p_{gas}/p_{mag}$

White contours: toroidal mgnetic field

arrows: poloidal velocities

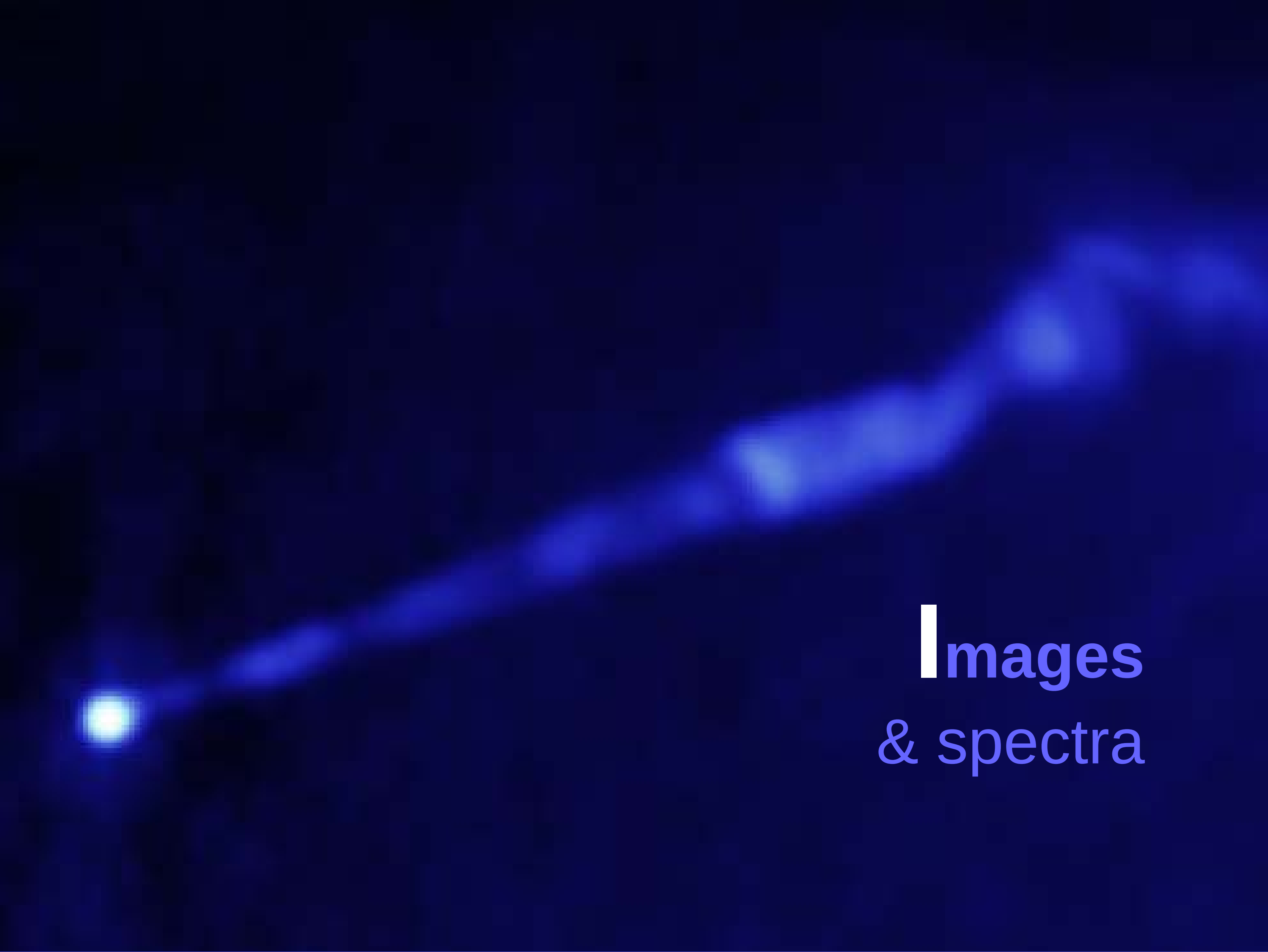
gravitomagnetic dynamo in Kerr

key ingredient: *$B_{initial}$ is uniform and parallel to z-axis (different from torus!)*

Thin *disk does* ***NOT*** *support growth of MRI!*

Jets are ***NOT*** *Poynting-flux dominated, rather driven by* ***gas pressure and Lorentz forces****!*

Mizuno et al. 2006, astro-ph/0609344

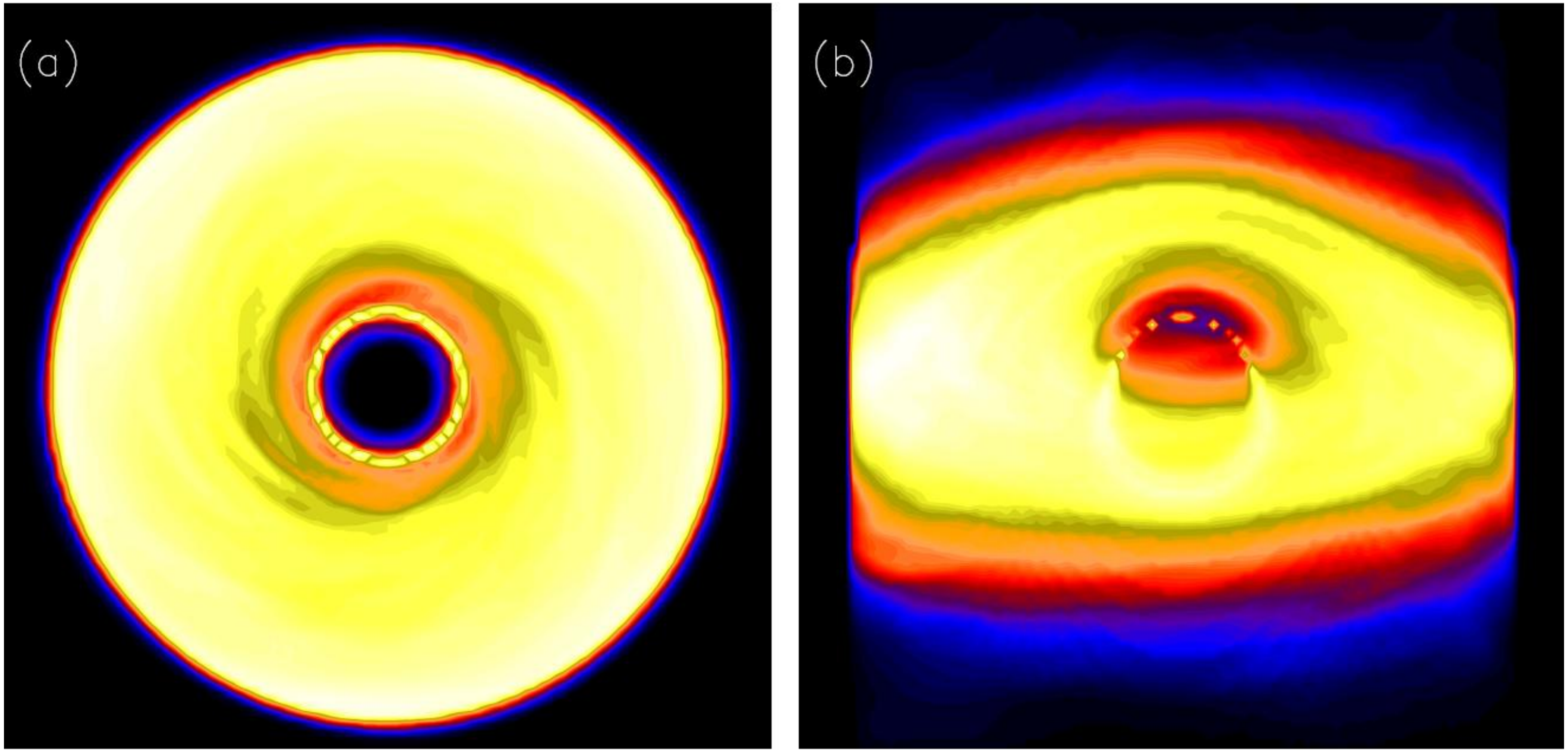


Images

& spectra

GR ray-tracing of non-rad GRMHD data

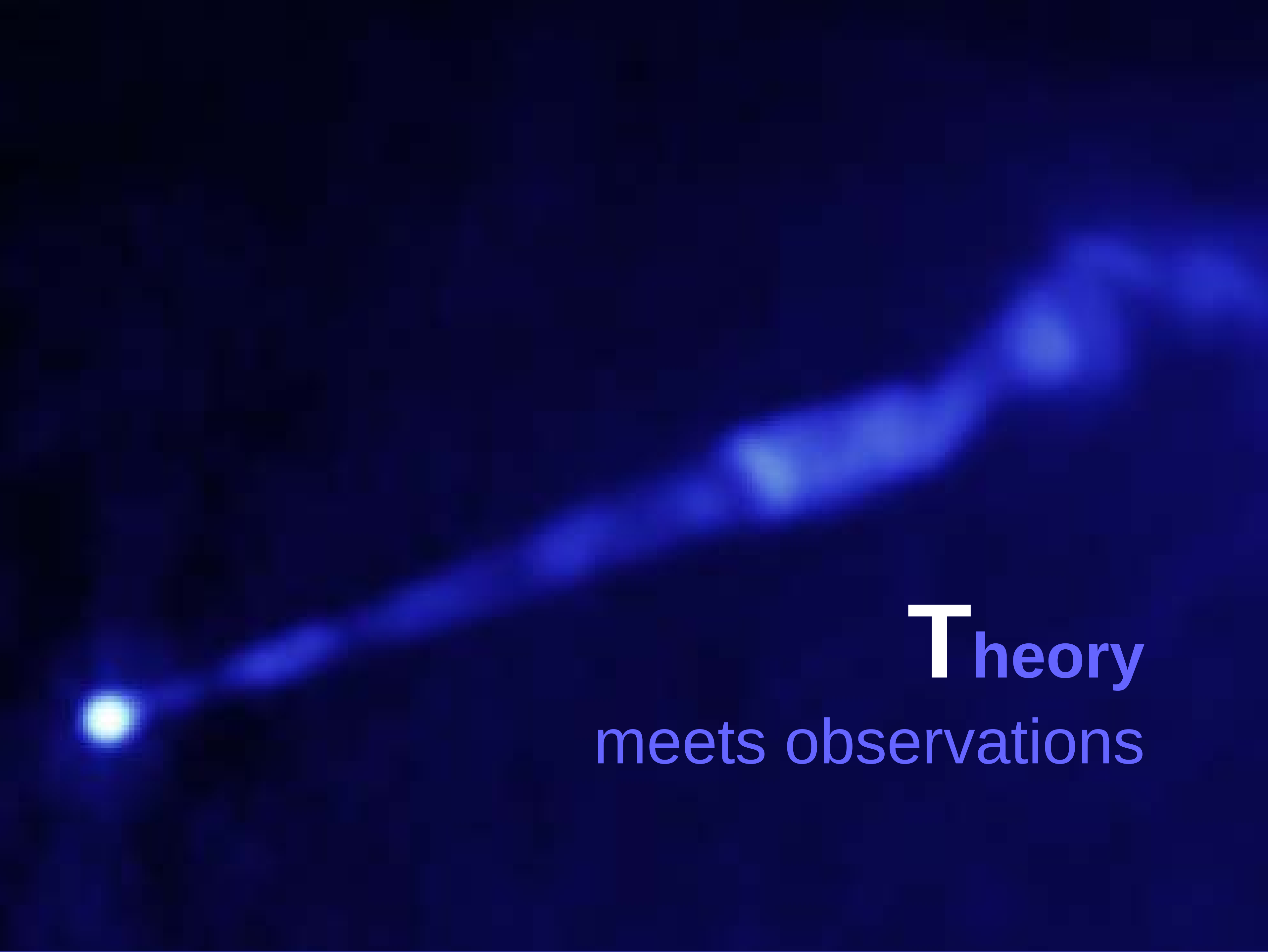
snapshots of optically-thin line emission, emission inside $r < 25\ r_g$



i = 0°   i = 70°

(Schwarzschild BH; light curves in paper, hot spots in disk emerge)

Schnittman et al. 2006


Theory
meets observations

Theory meets observations I

- funnel-wall jet with evacuated interior, „hollow jet“ (De Villier et al. 2002)
- BZ model fits better obs. Constraint than BP scenario (Blandford & Znajek 1977)
- thin Keplerian disk generates two jets (Mizuno et al. 2006, astro-ph/0609344)

- VLBI of M87 shows asymmetric edge-brightening indicating hollow jet (Krichbaum et al. 2005)
- small size of jet base (Krichbaum et al. 2005)
- Would explain inner, denser jet closer to z-axis

Theory meets observations II

- helical KH instabilities induced from rotations at jet base
- MHD Kink instabilities (Appl 1996)
- Kink conditions not satisfied (McKinney 2006)
- collimation due to hot corona by p_{rad} (Hawley SAF talk); by Lorentz forces; by disk wind (McKinney 2006)

- S-shaped jet structures, e.g. 3C 120 (Krichbaum et al. 2006)
- explains sudden curved jets
- stability of jets
- collimated jets

Theory meets observations III

- disk precession caused by Lense-Thirring or binary SMBH system

  [Mizuno et al. 2006:

  initial precessional perturbation propagates through jet as helical structure]

- helical jet structures (e.g. Britzen et al. 2001, Lobanov & Roland 2005)

Summary
& Outlook

Summary

- rotating space-time as **key ingredient**
- best metric available: **Kerr solution** (*fixed background*)
- very high spins: $a \sim 0.9 \ldots 0.998\ M$
- non-pathological coordinate frame recommended
- applications: AGN-Jets, BHXB-Jets, collapsars, GRBs
- accretion: MRI, magnetic turbulence MHD dominance in accretion and jets
- Is BZ process a more powerful driver?
- Jet base: paraboloidal jet, foot point near ergosphere
- Simulations now produce high Γ up to 1000
- however: **ideal MHD** results are **preliminary**

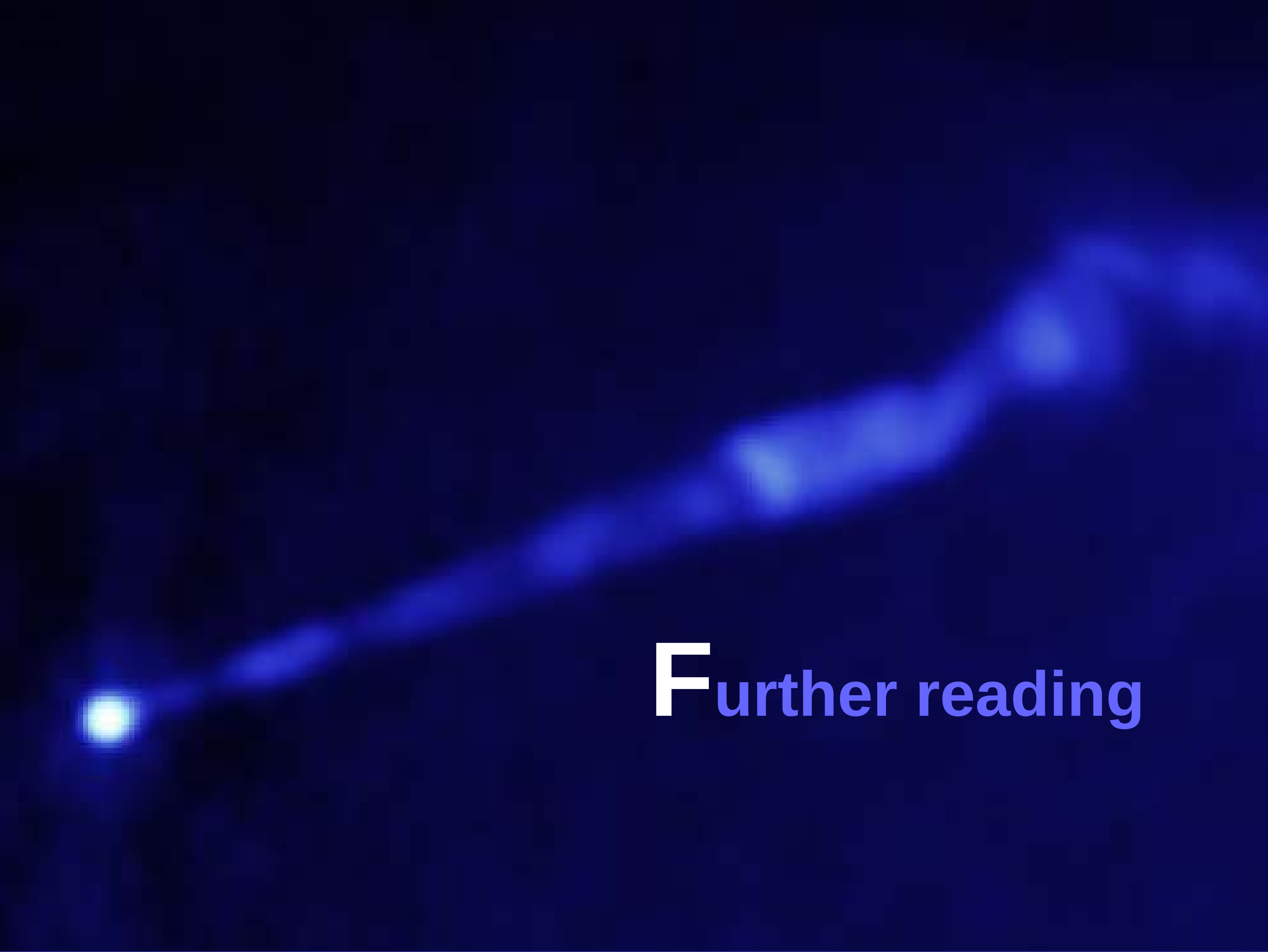
Outlook

theory

- **initial** magnetic field configuration?
- **high-energetic** particle network
- **two-component** plasma physics: thermal ions + relativistic electrons
- use **AMR** codes
- GRMHD in **strong** field limit
- **dissipative, radiative** GRMHD

observation

- **mm-VLBI**: GMVA, APEX, soon ALMA, VSOP; towards $\lambda < 3$ mm
- **leptonic vs. hadronic** jets: AMANDA, soon ICECUBE


Further reading

Web resources by A. Müller

- This talk as pdf:
  http://www.mpe.mpg.de/~amueller/downloads/talks/pdf/MPIfR_2006.pdf
- PhD thesis: *(BH astrophysics: MHD on the Kerr geometry, 2004)*
  http://www.mpe.mpg.de/~amueller/downloads/PhD/PhD_AMueller.pdf
- German online dictionary for astrophysics (relaunch in 2007: 500 entries)
  http://www.mpe.mpg.de/~amueller/lexdt.html
- German web articles on black holes etc.
  http://www.mpe.mpg.de/~amueller/astrodt.html