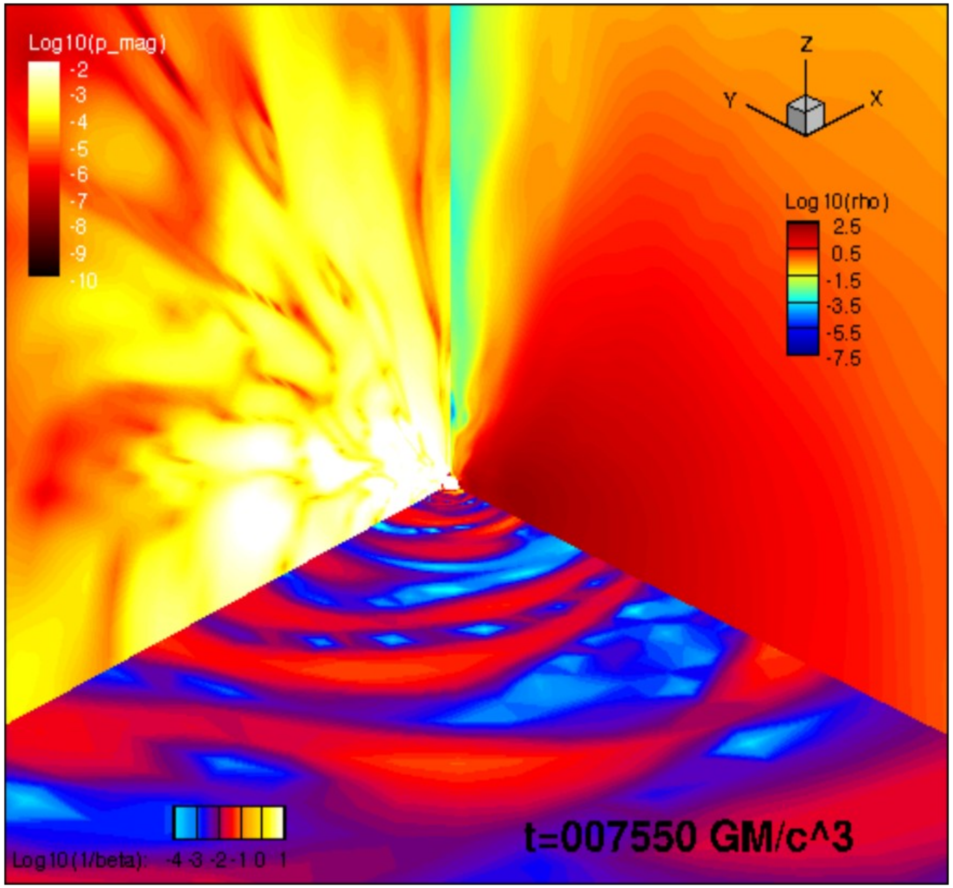
General-relativistic magnetohydrodynamics

Accretion flows onto Black holes and jet launch



Akira MIZUTA (RIKEN)

References
AM, Ebisuzaki, Tajima, and Nagataki, MNRAS 479 2534(2018)
the case of BH spin a=0.9
AM+ in prep.
parameter study in BH spin (a)

2nd Toyama International Symposium
on "Physics at the Cosmic Frontier"
@ Toyama Univ.
4 March 2020

Astrophysical Jets

What are astrophyscal jets and key questions on them ?

– Jets are collimated outflows powered by ``central object ＋ accretion disk’’ in different scales of our Universe

– How do the accretion flows overcome gravity by central objects ?

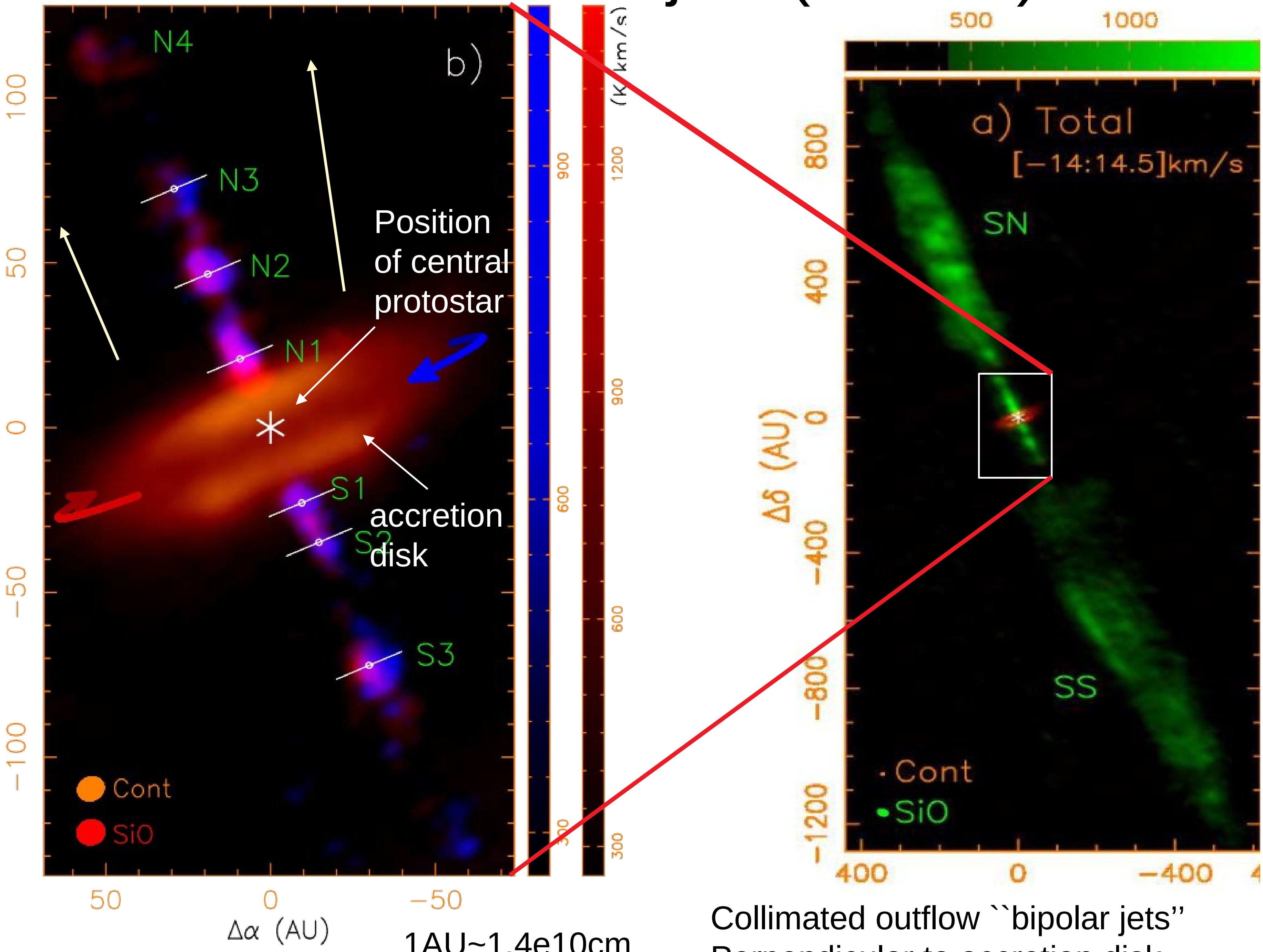
– How do the outflow become well collimated jets ?

	Central object	Bulk velocity	size
Protostellar jets	protostar	~100km/s	100AU~0.3pc
Micro-quasar jets	Black hole/ Neutro star 1-10M_{sun}	0.1-1c	0.1～1pc
Gamma-ray burst jets	Black hole (～ M_{sun})	~c(Γ~100)	~1pc
Active galactic jets	Supermassive black hole($10^{6-9}M_{sun}$)	~c(Γ~10)	pc~Mpc

c=3.e10cm/s (speed of loght), $\Gamma=(1-v^2/c^2)^{-1/2}$(Lorentz factor)

1AU=1.4e10cm , 1pc=3.e18cm, $M_{sun=}$2.e33g(solar mass)

Protostellar jets (HH212)



Position of central protostar

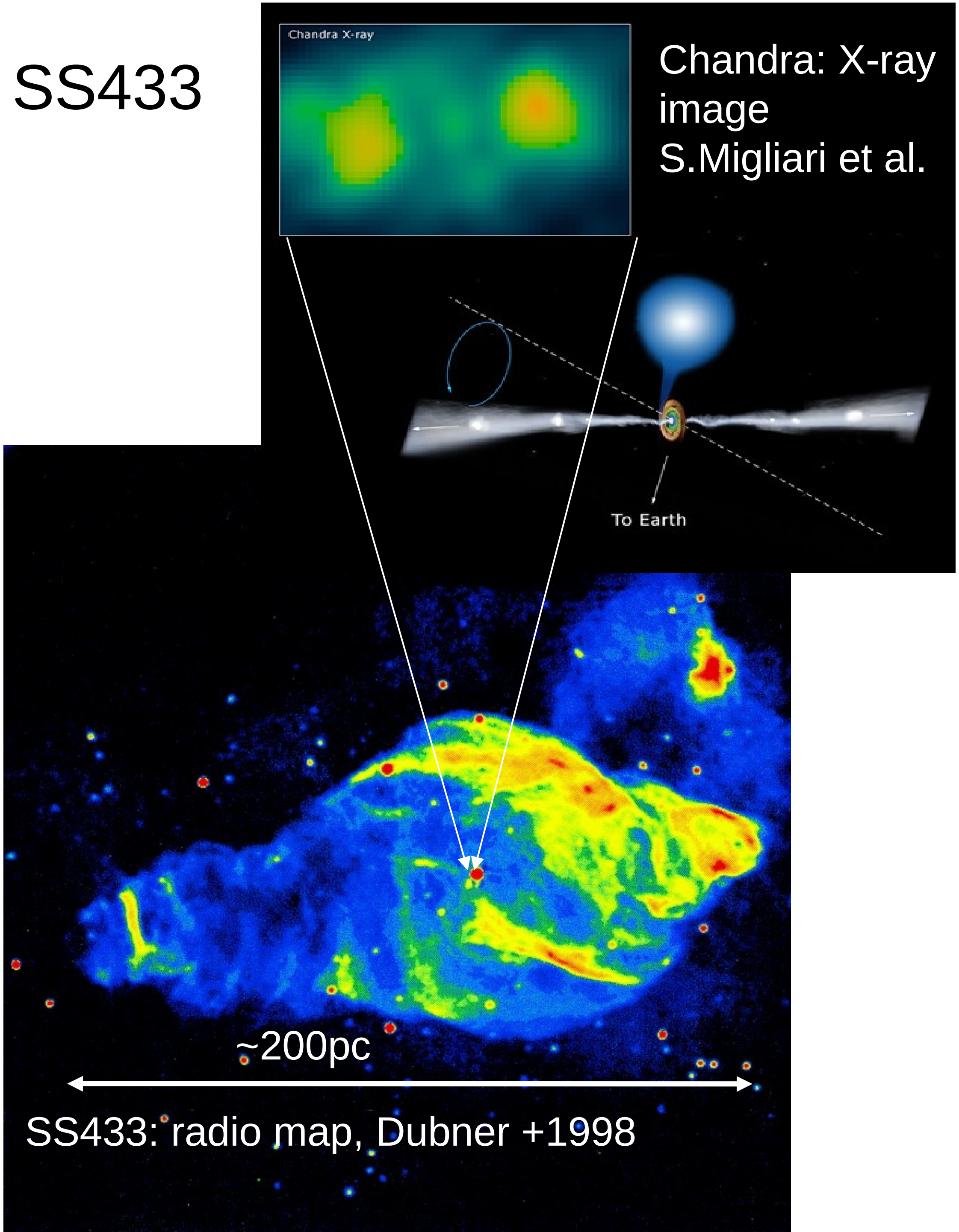
accretion disk

1AU~1.4e10cm

Collimated outflow ``bipolar jets''
Perpendicular to accretion disk
Lee + 2017 Nature Astronomy

Micro-quasar jets

SS433

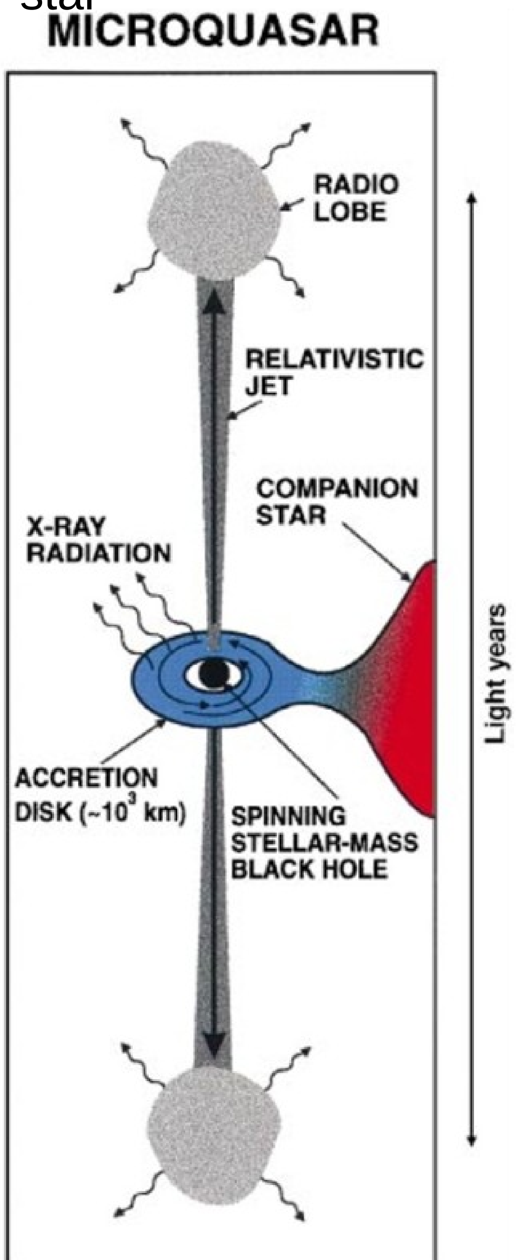


Chandra: X-ray image
S.Migliari et al.

~200pc

SS433: radio map, Dubner +1998

Accretion gas onto compact object (stellar mass black hole or netron star) are supplied from surface of companion star

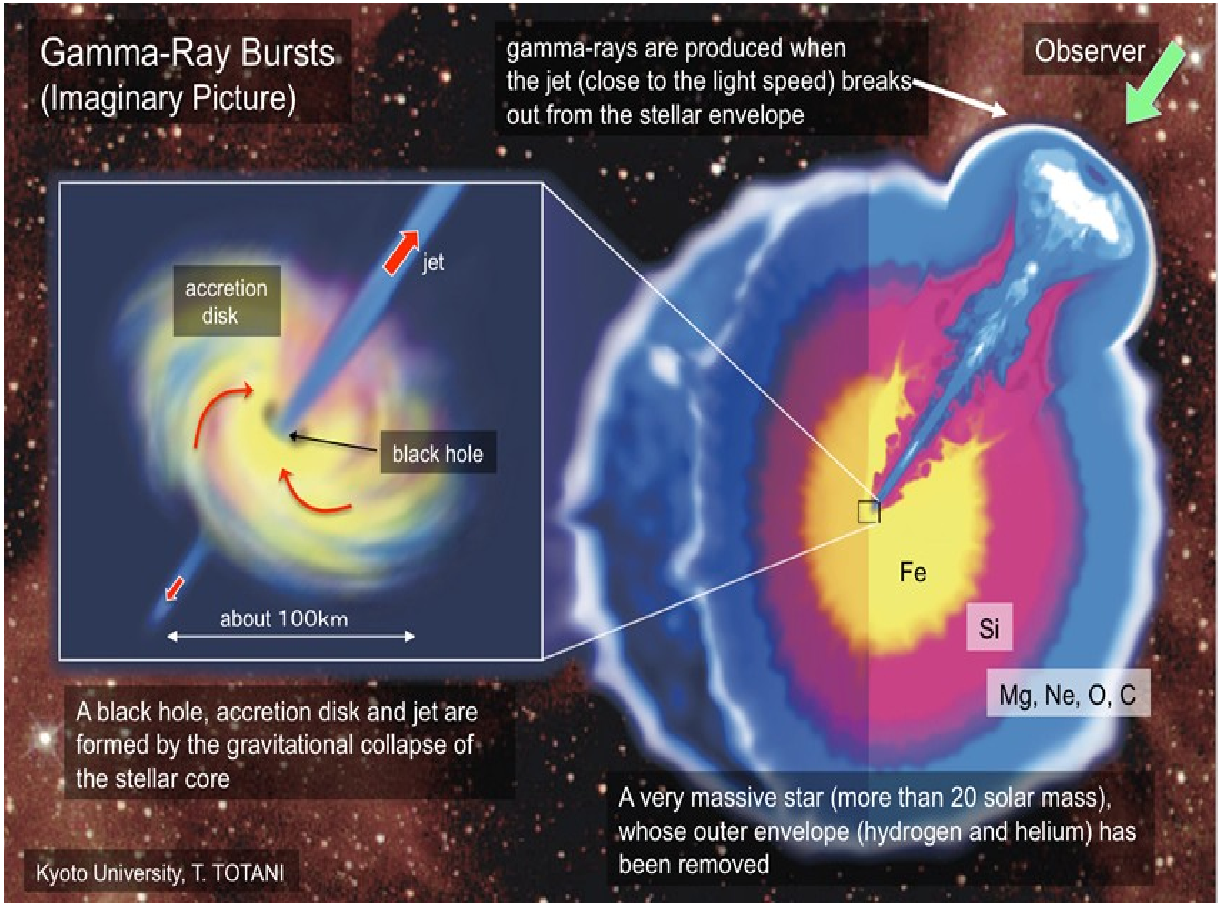


Accretion disk
+ jets
are common
feature with
protostar jets

Mirabel &
Rodriguez
1998 nature

Gamma-rat burst jets

long(t_γ >~2s)gamma-ray burst



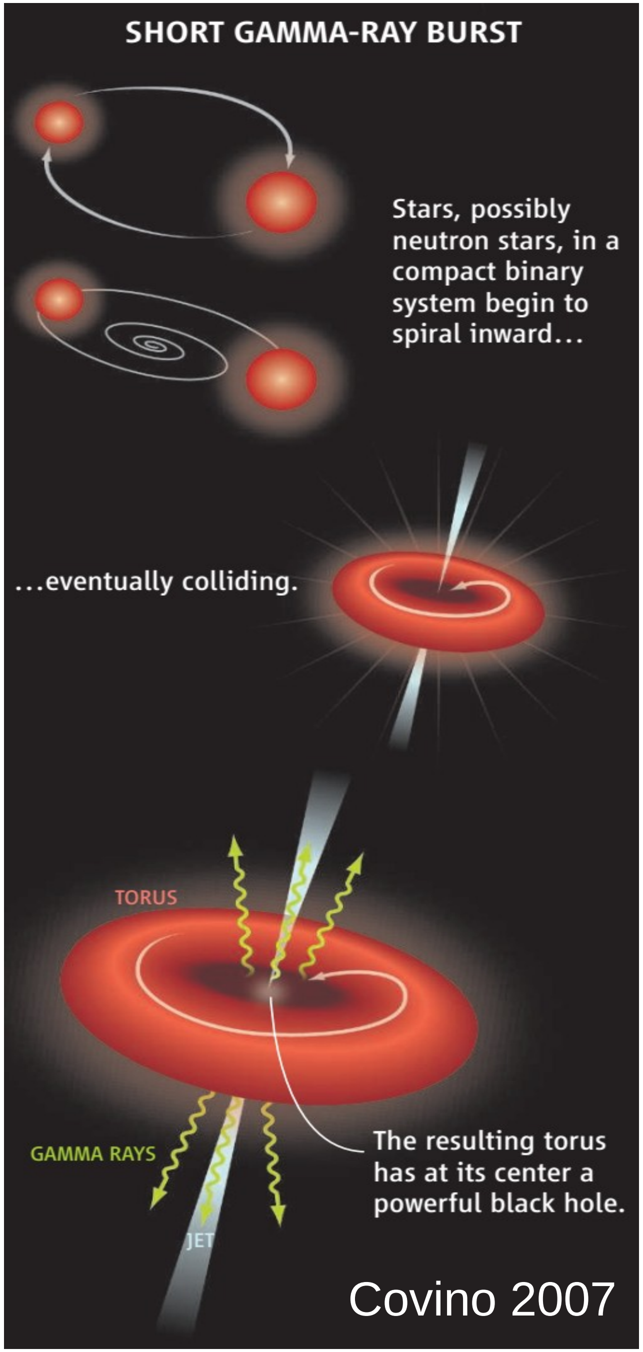
gamma-rays are produced when the jet (close to the light speed) breaks out from the stellar envelope

A black hole, accretion disk and jet are formed by the gravitational collapse of the stellar core

A very massive star (more than 20 solar mass), whose outer envelope (hydrogen and helium) has been removed

Kyoto University, T. TOTANI

Short (t_γ <~2s) gamma-ray burst



Stars, possibly neutron stars, in a compact binary system begin to spiral inward…

…eventually colliding.

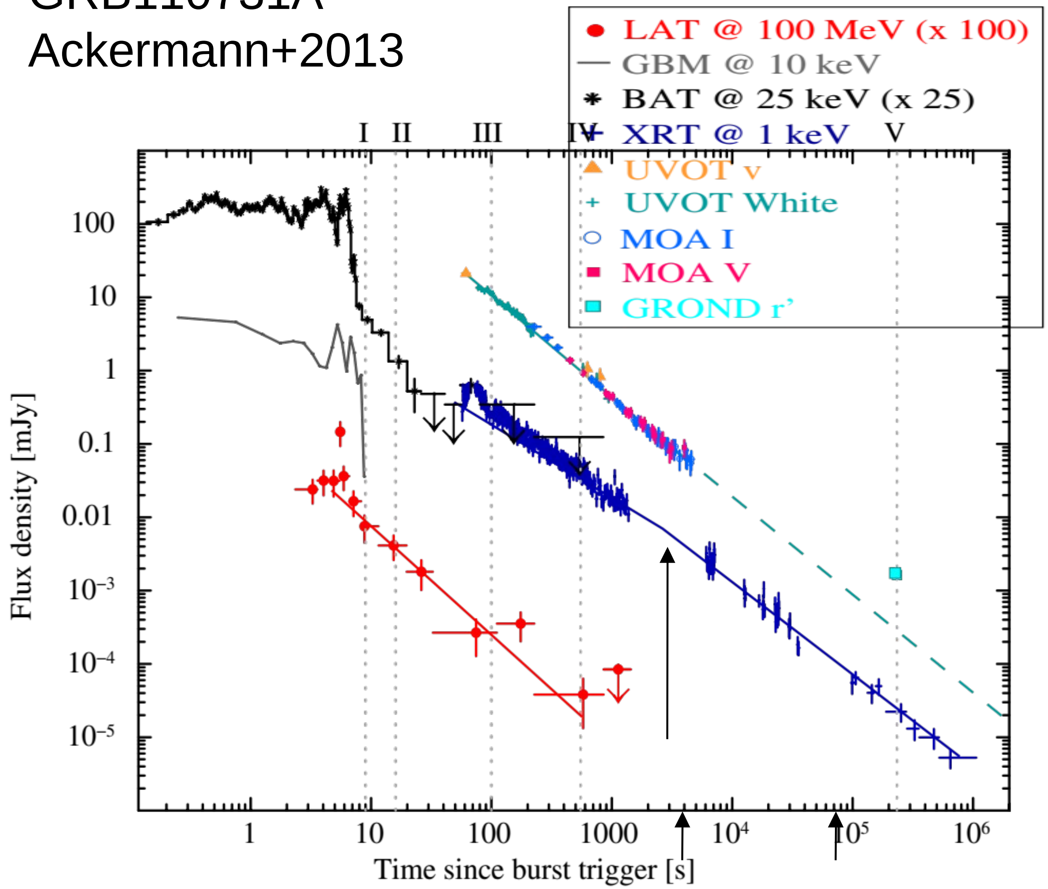
The resulting torus has at its center a powerful black hole.

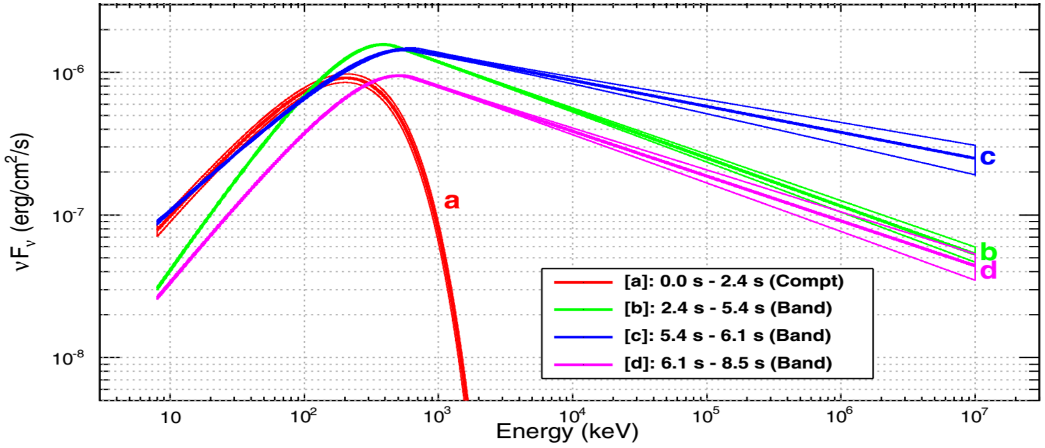
Covino 2007

Gamma-ray bursta associated with supernova
GRB 980425/SN1998bw(Galama+1998)
GRB 030329A /SN2003dh (Hjorth +2003)
GRB 060218/SN2006aj (Campana + 2006)
GRB 100316D/SN2010bh (Fan+2011)
GRB 171205A/SN2017iuk (Wang + 2018)

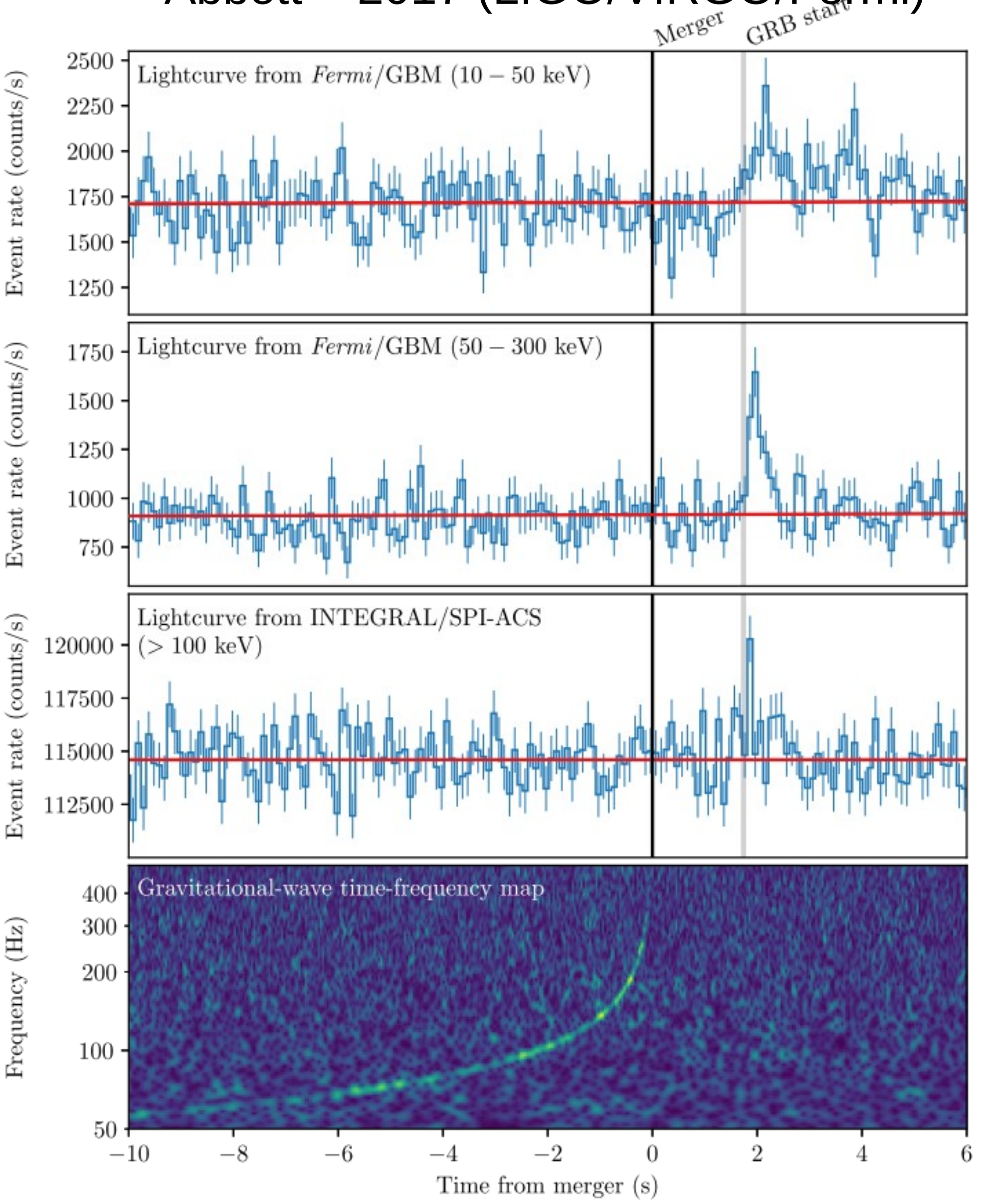
Gammar-ray burst jets (cont.)

GRB110731A
Ackermann+2013

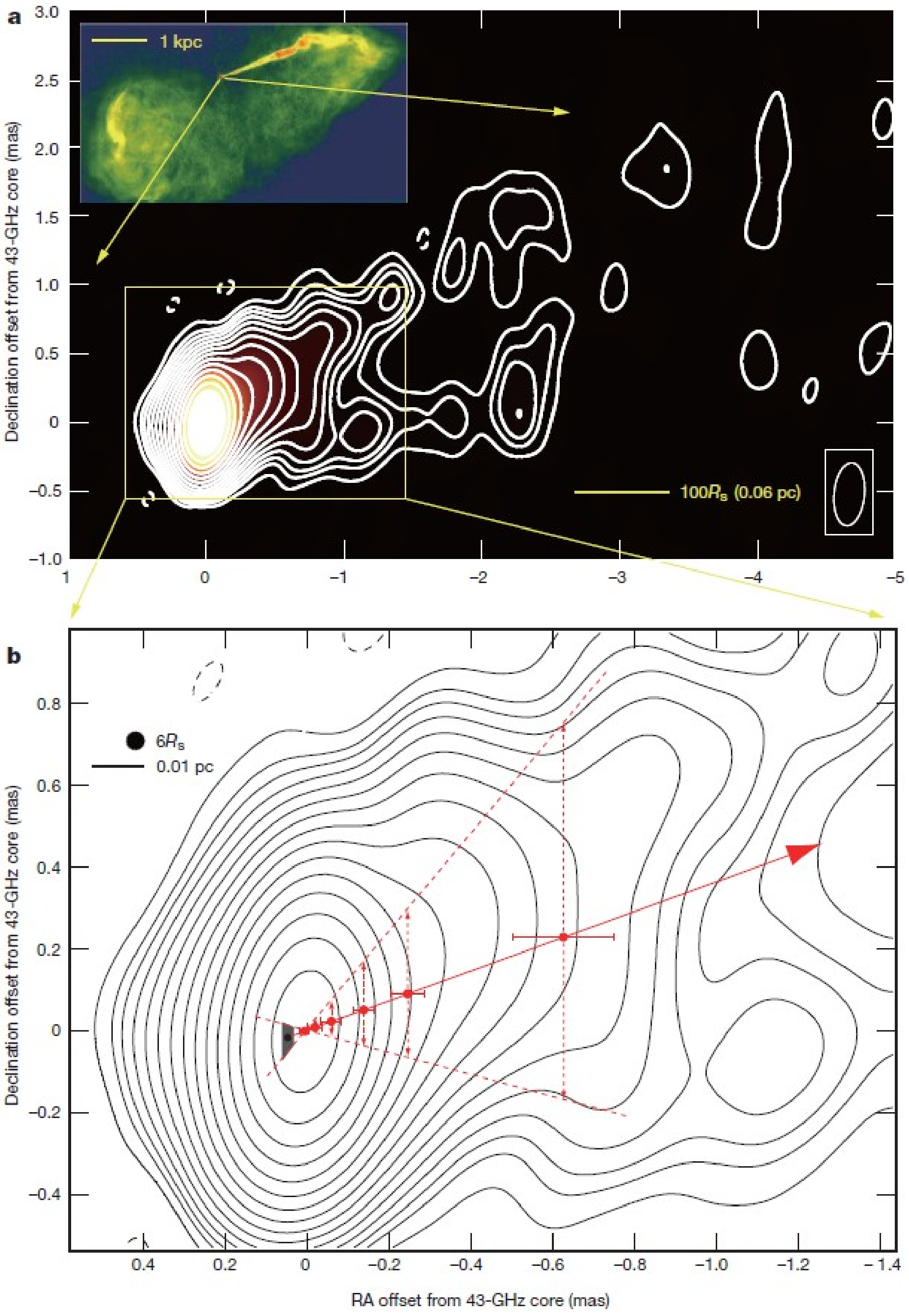




GW170817 GRB170817A
Abbott + 2017 (LIGO/VIRGO/Fermi)



Active Galactic Nuclei Jet

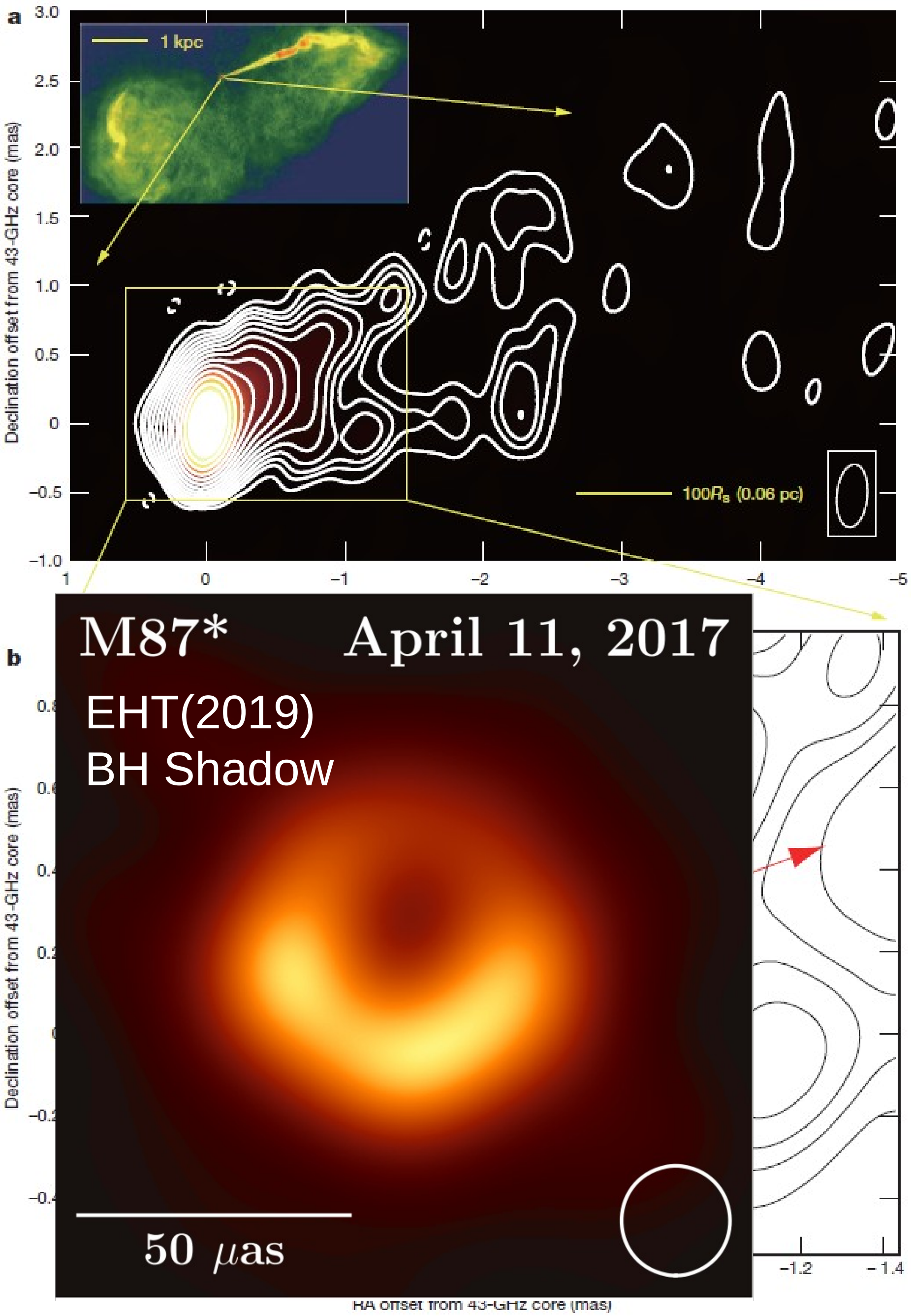


M87 radio observation   Hada +(2011)

Hilghlly collimated outflows from center of galaxy

- central engine
  - supermassive black hole
  - +
  - accretion disk
- relativistic outflows
  - Bulk Lorentz factor : Γ ~ 10
- multiwavelength emission
  - radio to high energy γ-rays
- detailed observation near BH
  - (EHT project since 2017)
- strong candidate of
  - ultra high energy cosmic ray accelerator
    - via Fermi acc. ? (1954)
    - or wake field acc.
    - (Ebisuzaki & Tajima 2014)

Active Galactic Nuclei Jet



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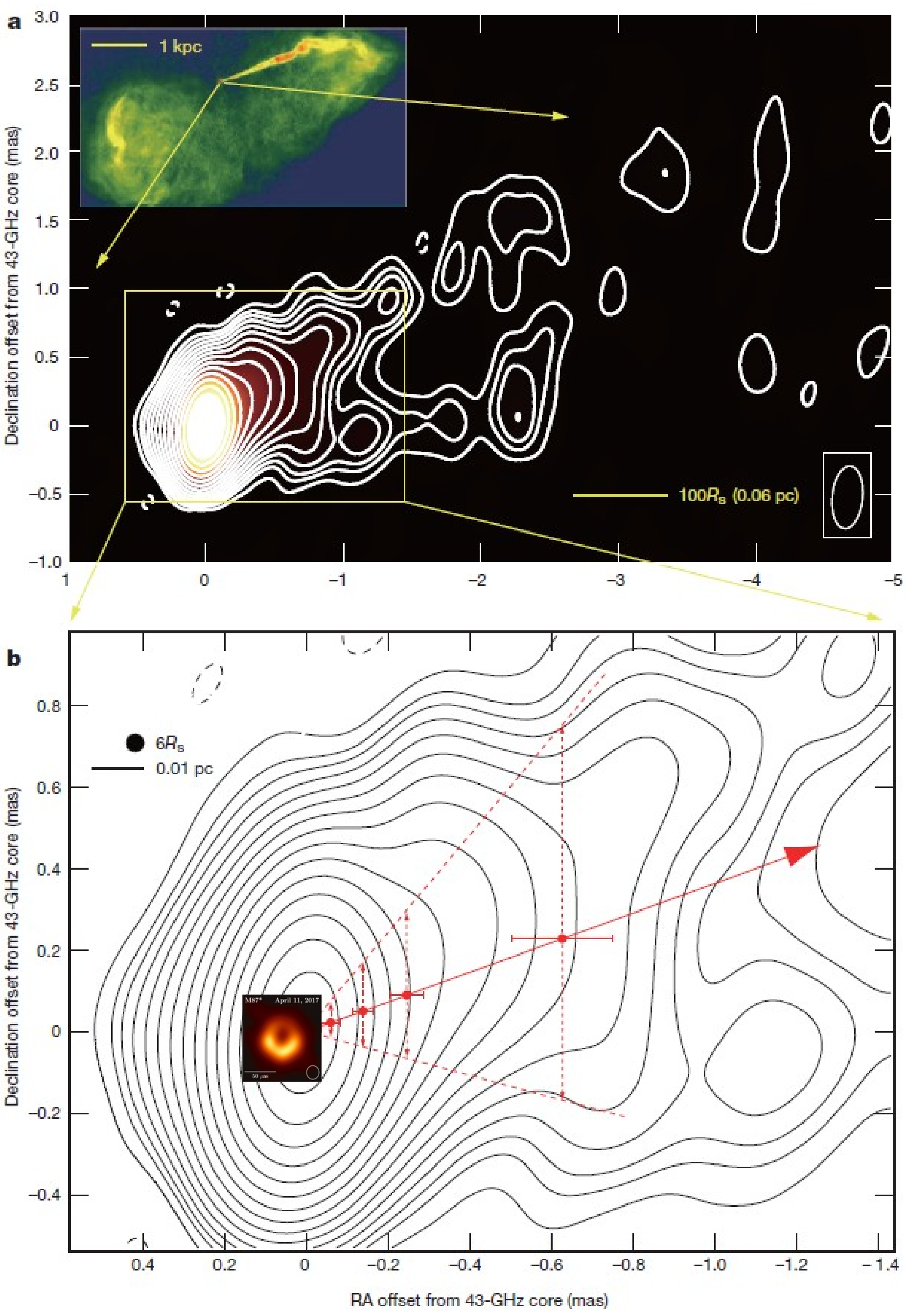
Active Galactic Nuclei Jet



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  or wake field acc.
  (Ebisuzaki & Tajima 2014)

Gas can not accrete onto central object w/o any viscous process

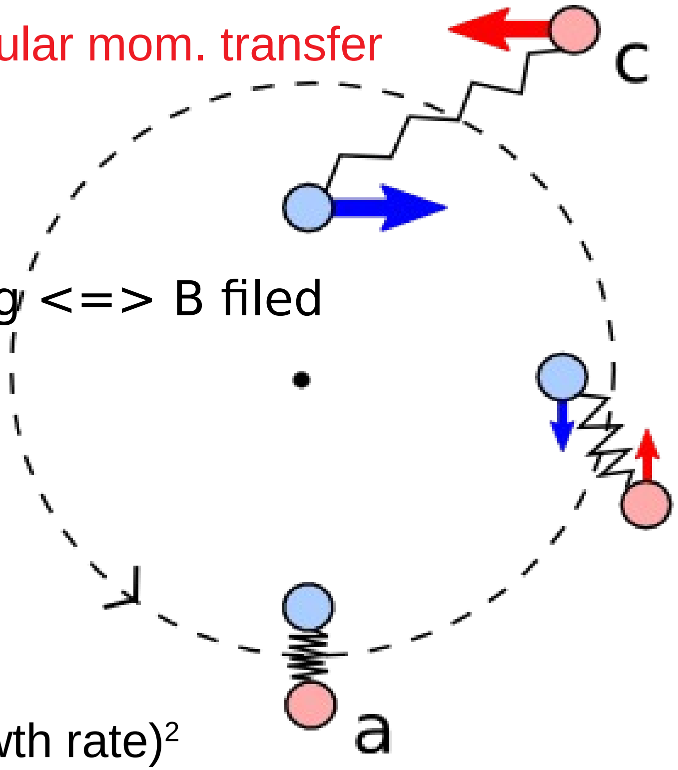
- Central object, such as protostars, neutron stars, and black holes(gravity source) and accretion disk system is common to produce collimated outflows, i.e. jets.
- Problem : How to throw away the angular momentum from the system ? Otherwise gas can not easily accrete onto central object because of angular momentum conservation law

- Interactions between planets, comets, and other small objects are negligible

ex) ``Solar system'' is very stable for 46 billion years due to less chance to exchange angular momentum between planets and other small objects around the sun.

- Accretion disk is gas object in which gas can easily exchange angular momentum each other
- Angular momentum can be transferred by viscous torques from inner part of the disk to the outer part.
- The key is magnetic field in the accretion disk.

Angular mom. Transfer by B-filed amplification in the disk



Magnetorotational instability (MRI)

- differentially rotating disk :

  $d\Omega_{disk}/dr < 0$

  $\Omega_{disk} \propto r^{-1.5}$:Kepler rotation

- $B \propto \exp(i\omega t)$
- MRI enhances **angular momentum transfer**

Velikhov (1959)
Chandrasekhal (1960)
Balbus &Hawley (1991)

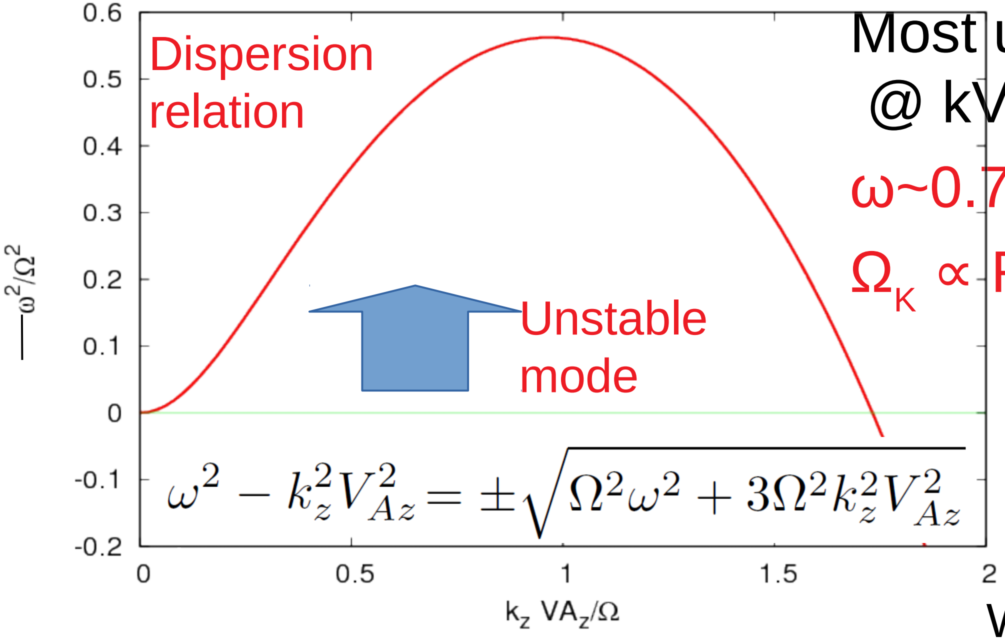
Unstable @
$0 < kV_a < 1.73\ \Omega_K$

Most unstable
@ $kV_a \sim \Omega_K$

$\omega \sim 0.75\Omega_K$

$\Omega_K \propto R^{-3/2}$,

$-$(growth rate)^2



$$\omega^2 - k_z^2 V_{Az}^2 = \pm\sqrt{\Omega^2\omega^2 + 3\Omega^2 k_z^2 V_{Az}^2}$$

Wave number

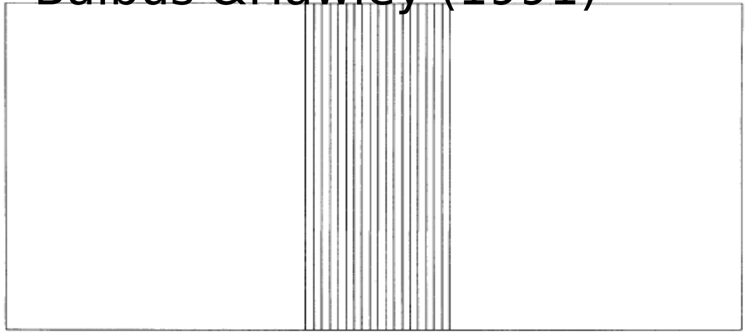


FIG. 3a

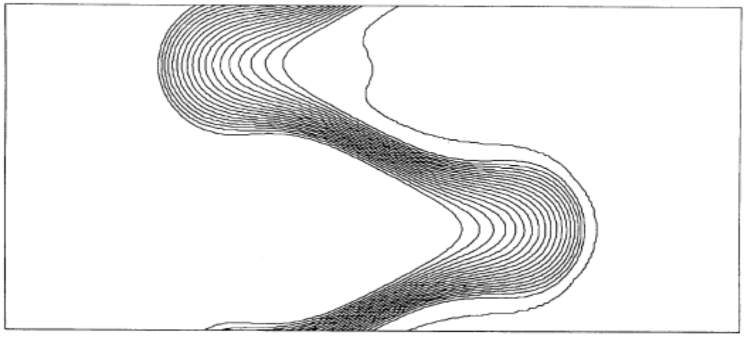
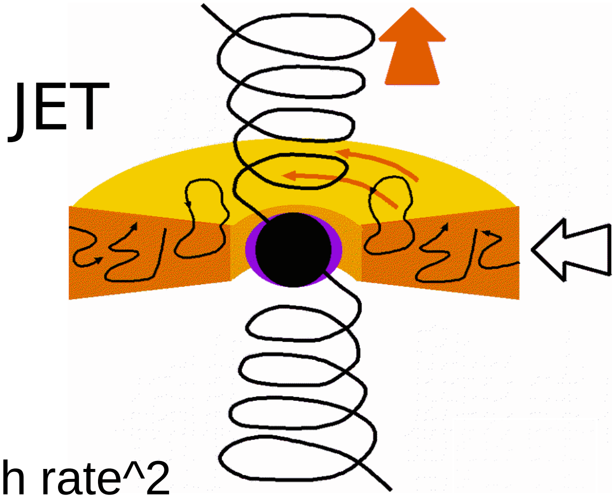


FIG. 3b

Black hole accretion flows and jets



Central engine (Black Hole(BH) + disk)

-Timevariability (Shibata +1990,
Balbus & Hawley1991)

-- MRI growth (B ↗ => Low beta state)

Magnetorotational instability

– differential roration : $d\Omega_{disk}/dr < 0$

$\Omega_{disk} \propto r^{-1.5}$:Kepler rotation

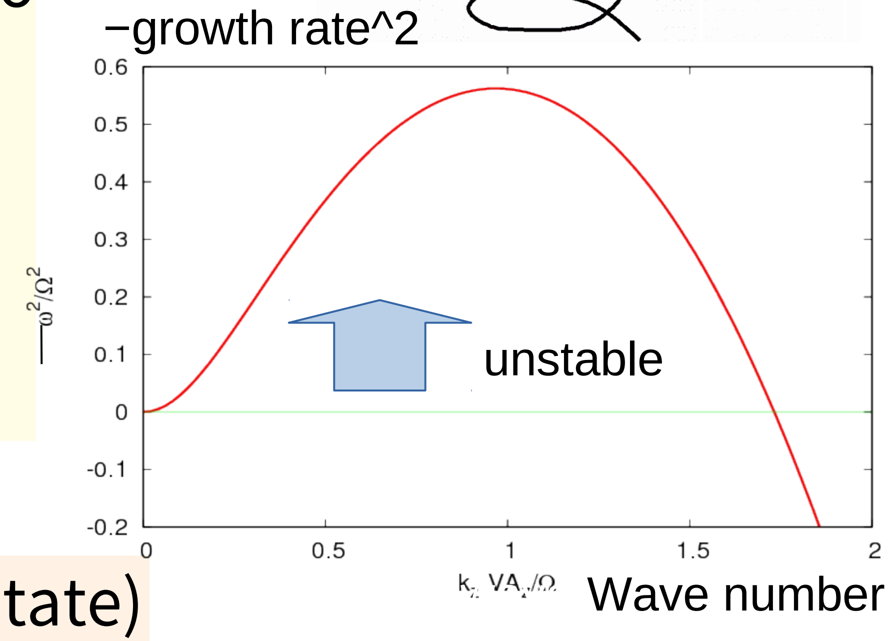
– $B \propto \exp(i\omega t)$

Unstable @ $0 < kV_a < 1.73\ \Omega_K$

Most unstable @ $kV_a \sim \Omega_K$ $\omega \sim 0.75\Omega_K$

– angular momentum transfer

-- dissipation of B (B ↘=> High beta state)



-- Shortest timescale of the system is MRI growth time : $1/\omega \sim 4/3\,\Omega_K$

-- Repeat cycle is ~10 Ω_K (Shi +2010)

Basic Equations : GRMHD Eqs.

GM=c=1, a: dimensionless Kerr spin parameter

$$\frac{1}{\sqrt{-g}}\partial_\mu(\sqrt{-g}\rho u^\mu) = 0$$

Mass conservation Eq.

$$\partial_\mu(\sqrt{-g}T^\mu_\nu) = \sqrt{-g}T^\kappa_\lambda \Gamma^\lambda{}_{\nu\kappa}$$

Energy-momentum conservation Eq.

$$\partial_t(\sqrt{-g}B^i) + \partial_j(\sqrt{-g}(b^i u^j - b^j u^i)) = 0$$

Induction Eq.

$$p = (\gamma - 1)\rho\epsilon$$

EOS (γ=4/3)

Constraint equations.

$$\frac{1}{\sqrt{-g}}\partial_i(\sqrt{-g}B^i) = 0$$

No-monopoles constraint

$$u_\mu b^\mu = 0$$

Ideal MHD condition

$$u_\mu u^\mu = -1$$

Normalization of 4-velocity

Energy-momentum tensor

$$T^{\mu\nu} = (\rho h + b^2)u^\mu u^\nu + (p_{\mathrm{g}} + p_{\mathrm{mag}})g^{\mu\nu} - b^\mu b^\nu$$

$$p_{\mathrm{mag}} = b^\mu b_\mu/2 = b^2/2$$

$$b^\mu \equiv \epsilon^{\mu\nu\kappa\lambda}u_\nu F_{\lambda\kappa}/2 \quad B^i = F^{*it}$$

GRMHD code (Nagataki 2009,2011, see also Noble 2006)

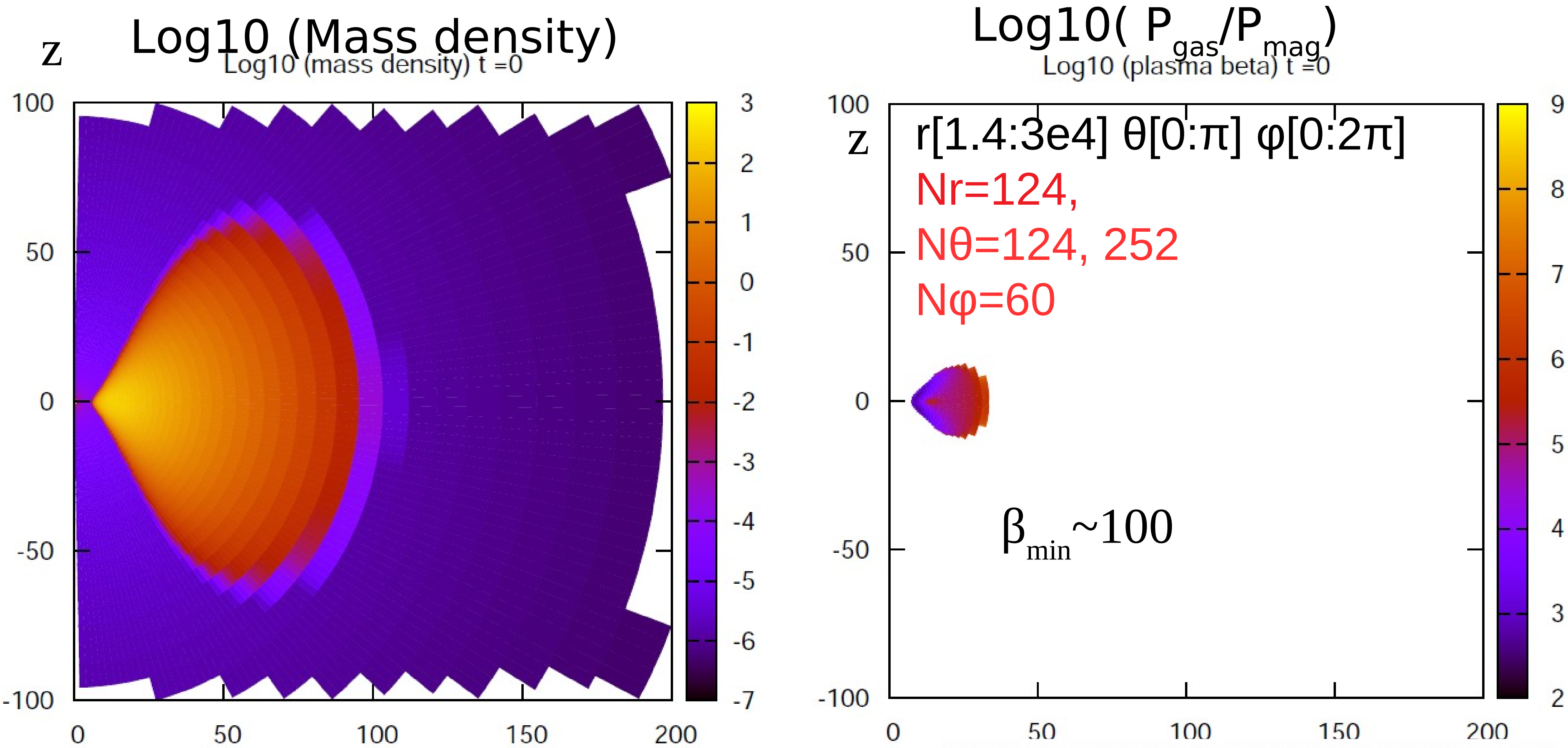
Kerr-Schild metric (no singular at event horizon)

HLL flux, 2nd order in space (van Leer), 2nd or 3rd order in time

See also, Gammie +03, Noble + 2006

Flux-interpolated CT method for divergence free

Initial Condition



Log10 (Mass density)

Log10(P_{gas}/P_{mag})

r[1.4:3e4] θ[0:π] φ[0:2π]

Nr=124,

Nθ=124, 252

Nφ=60

β_{min}~100

$$A_\phi \propto \max\left[\rho/\rho_{\max} - 0.2, 0\right]$$

Fisbone-Moncrief (1976) solution – hydrostatic solution of tori around rotating BH (**a=0.9**, rH~1.44), $l_* \equiv -u^t u_\phi$ =const =4.45, r_{in}=6. > r_{ISCO}

With maximum 5% random perturbation in thermal pressure.

Units L : Rg=GM/c^2 (=Rs/2), T : Rg/c=GM/c^3

~9.0x10^{14}cm(M_{BH}/6x$10^9$$M_{sun}$) ~3000s ($M_{BH}$/6x$10^9$$M_{sun}$)

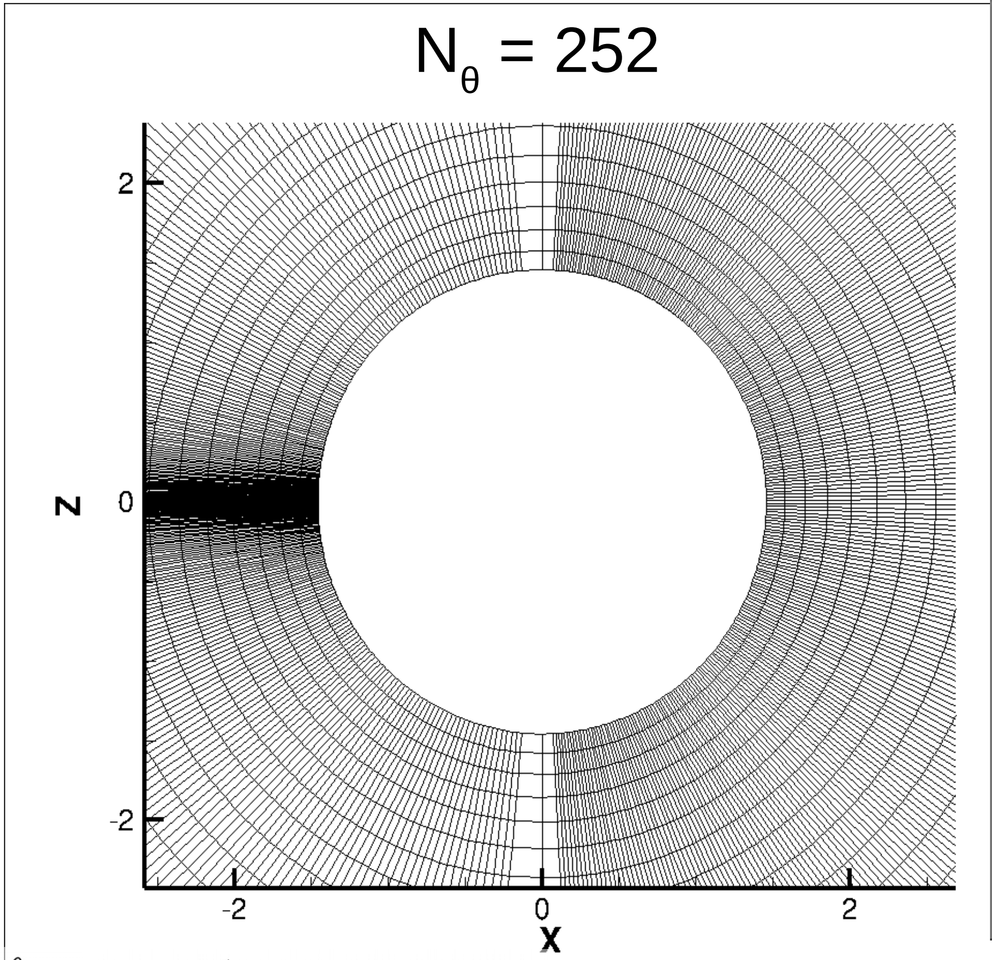
Grids to capture MRI fastest growing mode

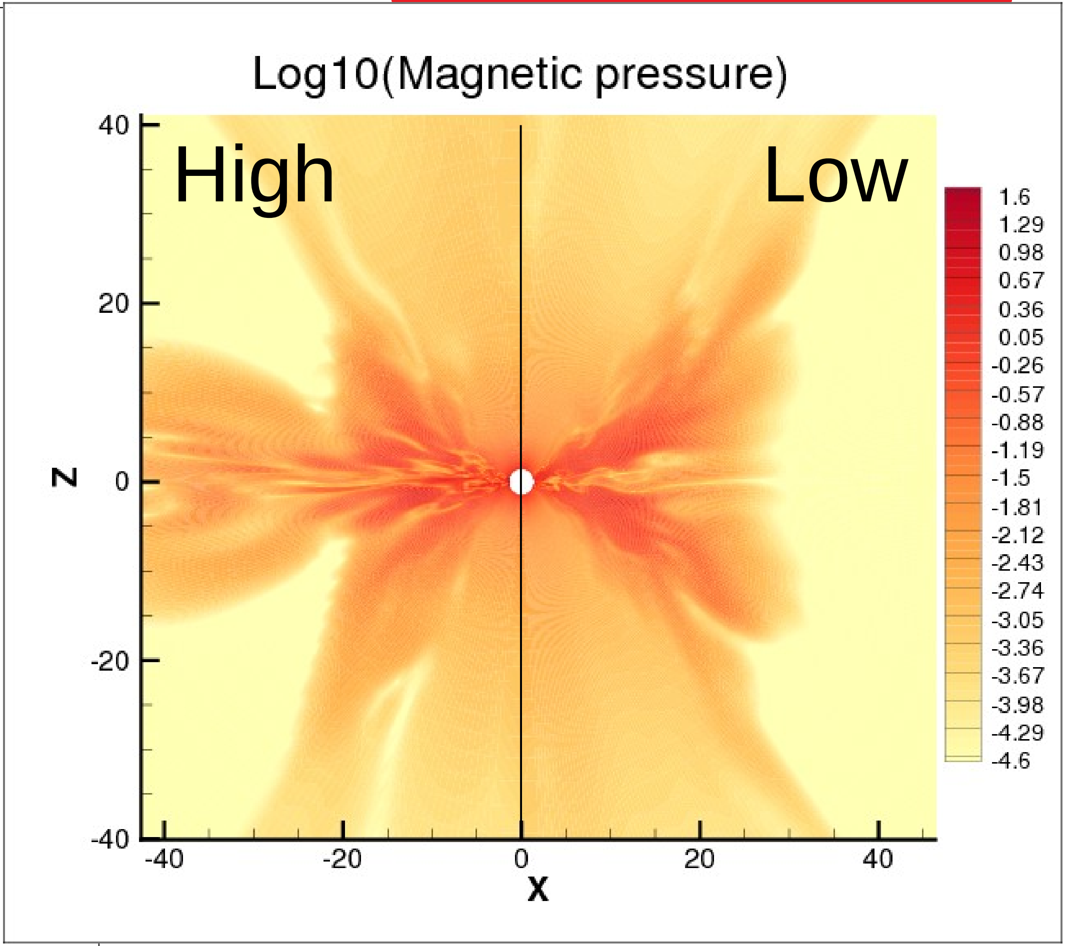
Wavelength of fastest growing mode in the disk

$\lambda_{MRI} = 2\pi <C_{az}> / \Omega_K (R) \sim 0.022 (R/R_{ISCO})^{1.5}$

$<C_s> \sim <C_{A z}> \sim 10^{-3}$ c

R_{ISCO} (a=0.9)=2.32





$$\theta = \pi x_2 + \frac{1}{2}(1-h)\sin(2\pi x_2)$$

x_2 = [0:1] Δx_2=cost

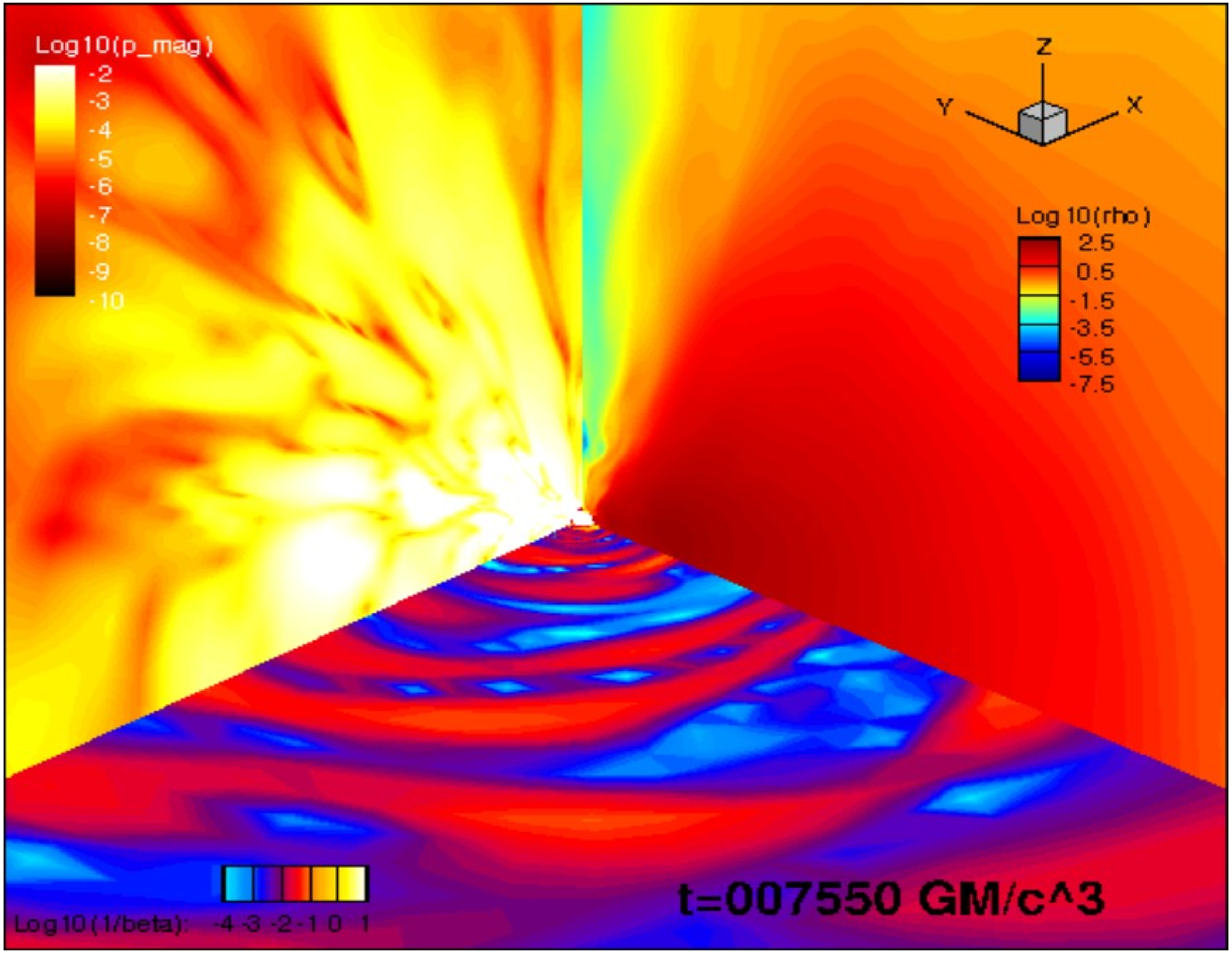
h=0.2

$\Delta\theta$=cost

h=1

McKinney and Gammie 2004

Magnetized jet launch



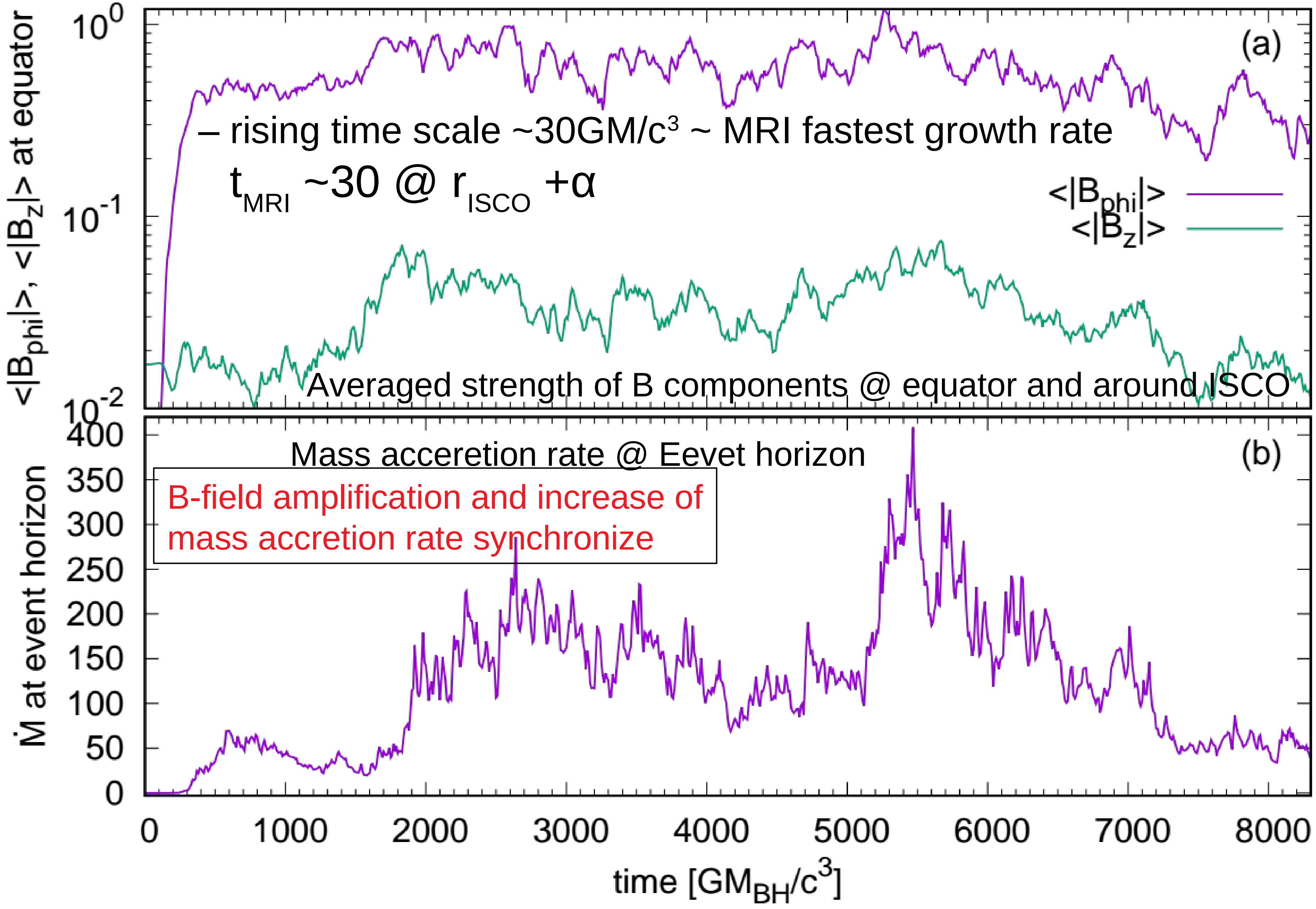
Disk : Fishbone Moncrief solution, spin parameter **a=0.9 (0.7, 0.5, 0.3, 0.1)**

spherical coordinate R[0.98 r_H(a):3e4] θ[0:π] φ[0:2π]

[NR=124,**Nθ=252, Nφ=60**] r=exp(n_r), θ : **non-niform (concentrate @ equator)**

dφ~6^o: uniform Poloidal B filed, β_min=100

B-filed amplification & mass accretion (a=0.9 case)



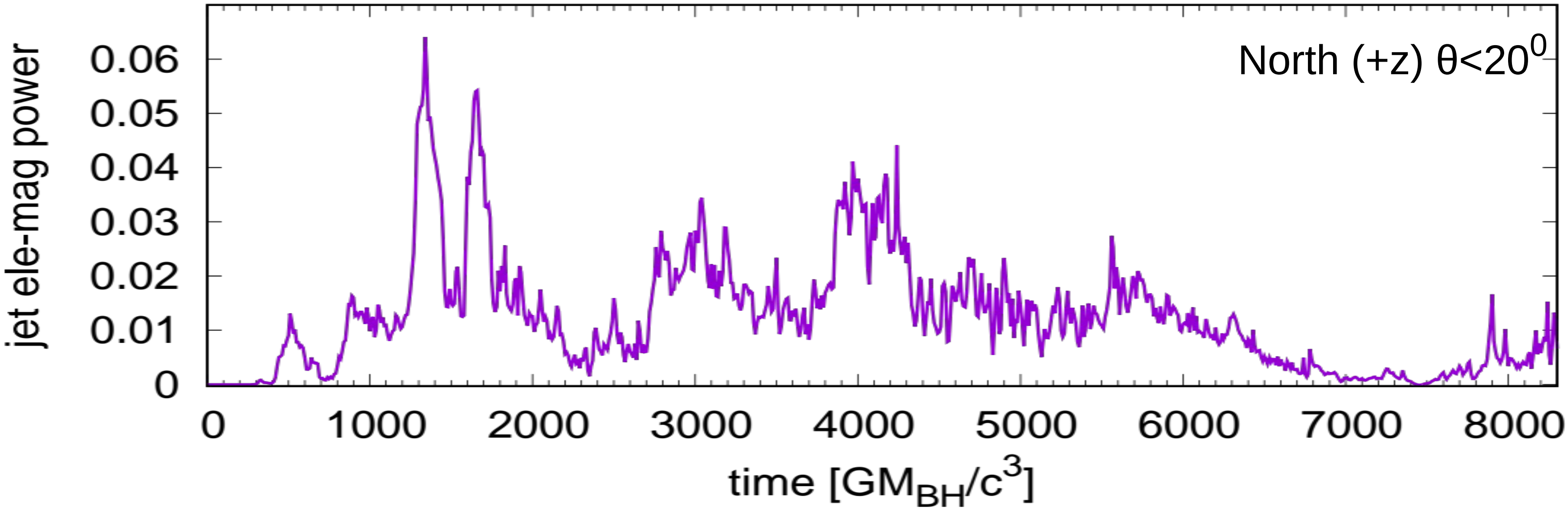
– rising time scale ~30GM/c^3 ~ MRI fastest growth rate

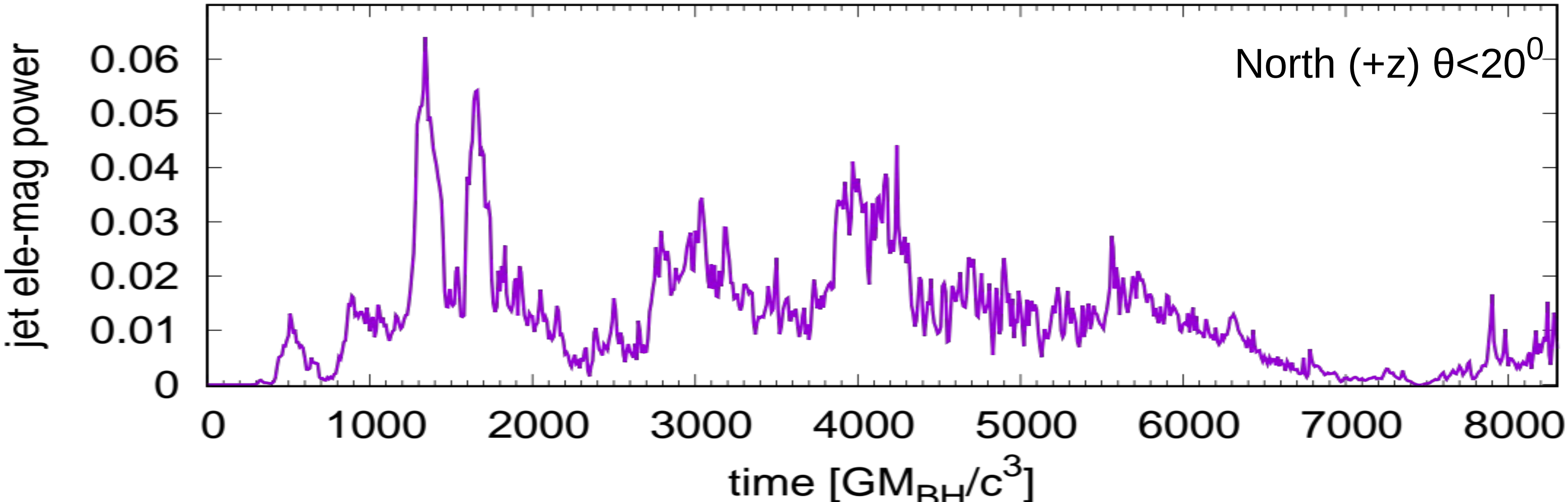
t_{MRI} ~30 @ r_{ISCO} +α

Averaged strength of B components @ equator and around ISCO

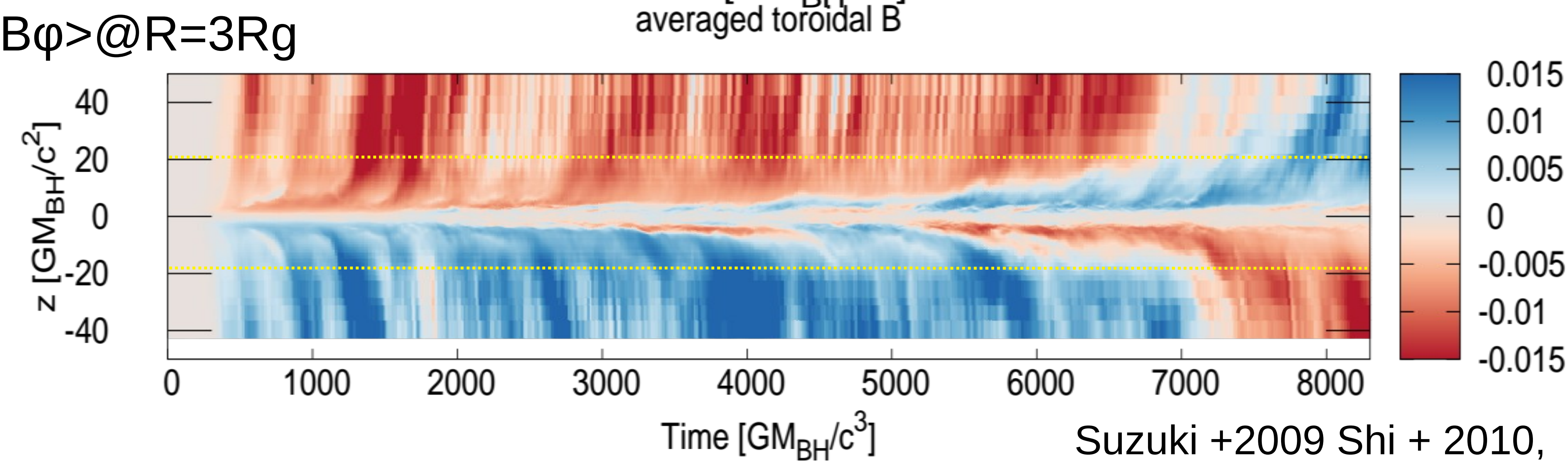
Mass acceretion rate @ Eevet horizon

B-field amplification and increase of mass accretion rate synchronize

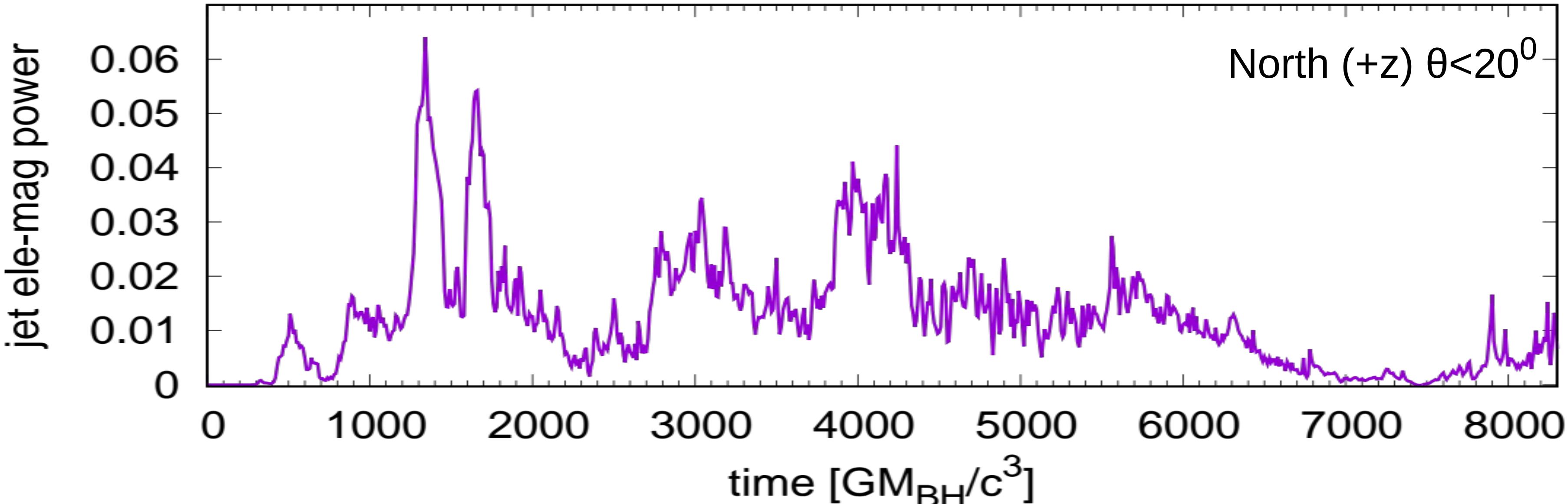

North (+z) θ<20⁰
jet ele-mag power
0
0.01
0.02
0.03
0.04
0.05
0.06
0
1000
2000
3000
4000
5000
6000
7000
8000
time [GM_BH/c^3]



<Bφ>@R=3Rg

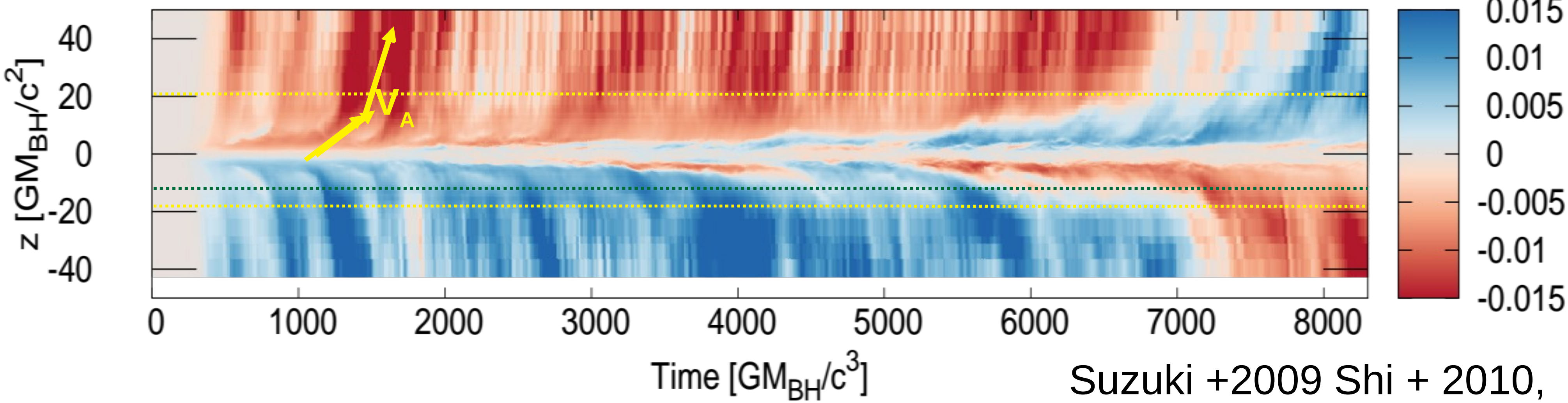


Suzuki +2009 Shi + 2010,
Machida +2013



<Bφ>@R=3Rg

averaged toroidal B



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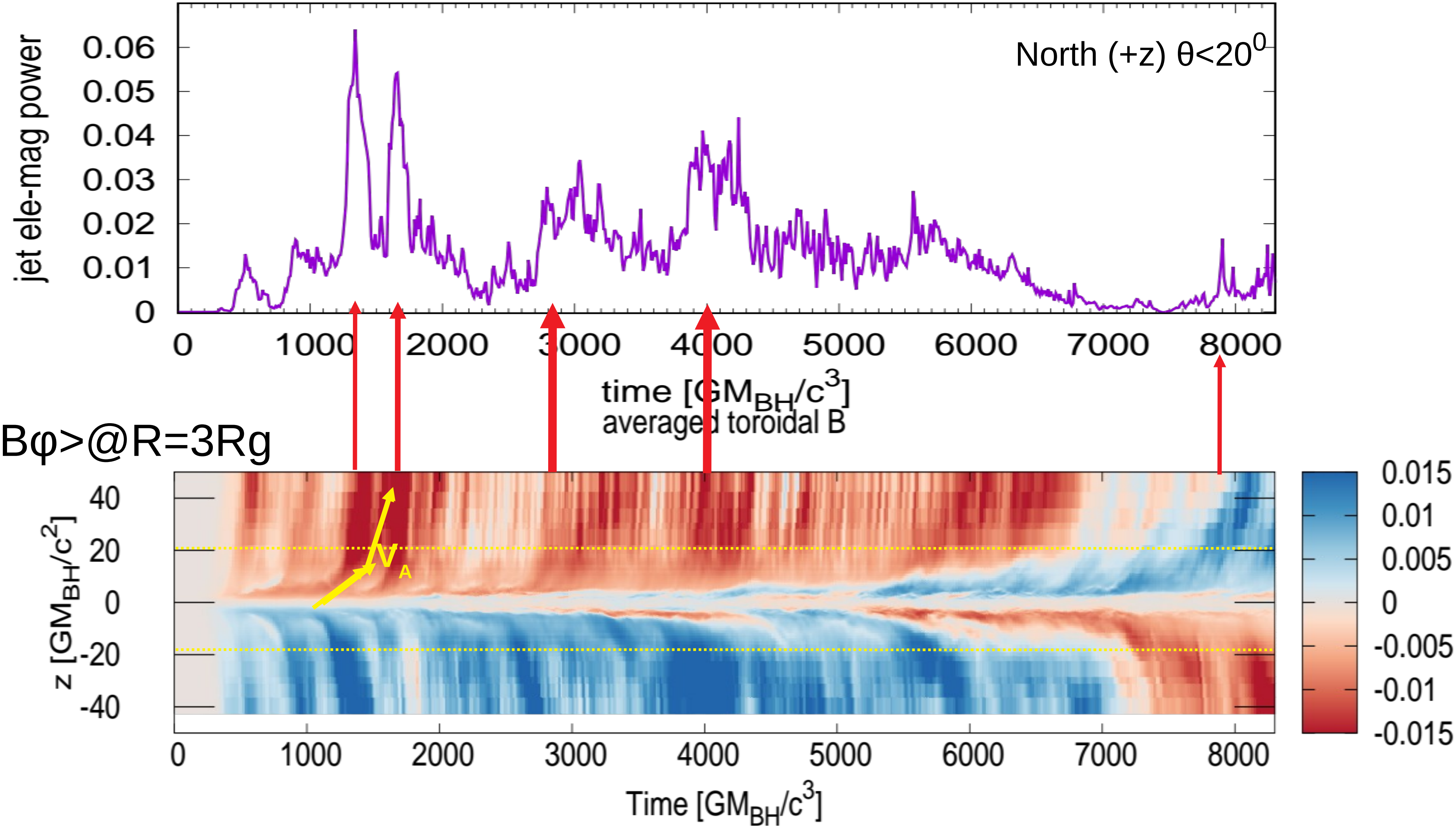
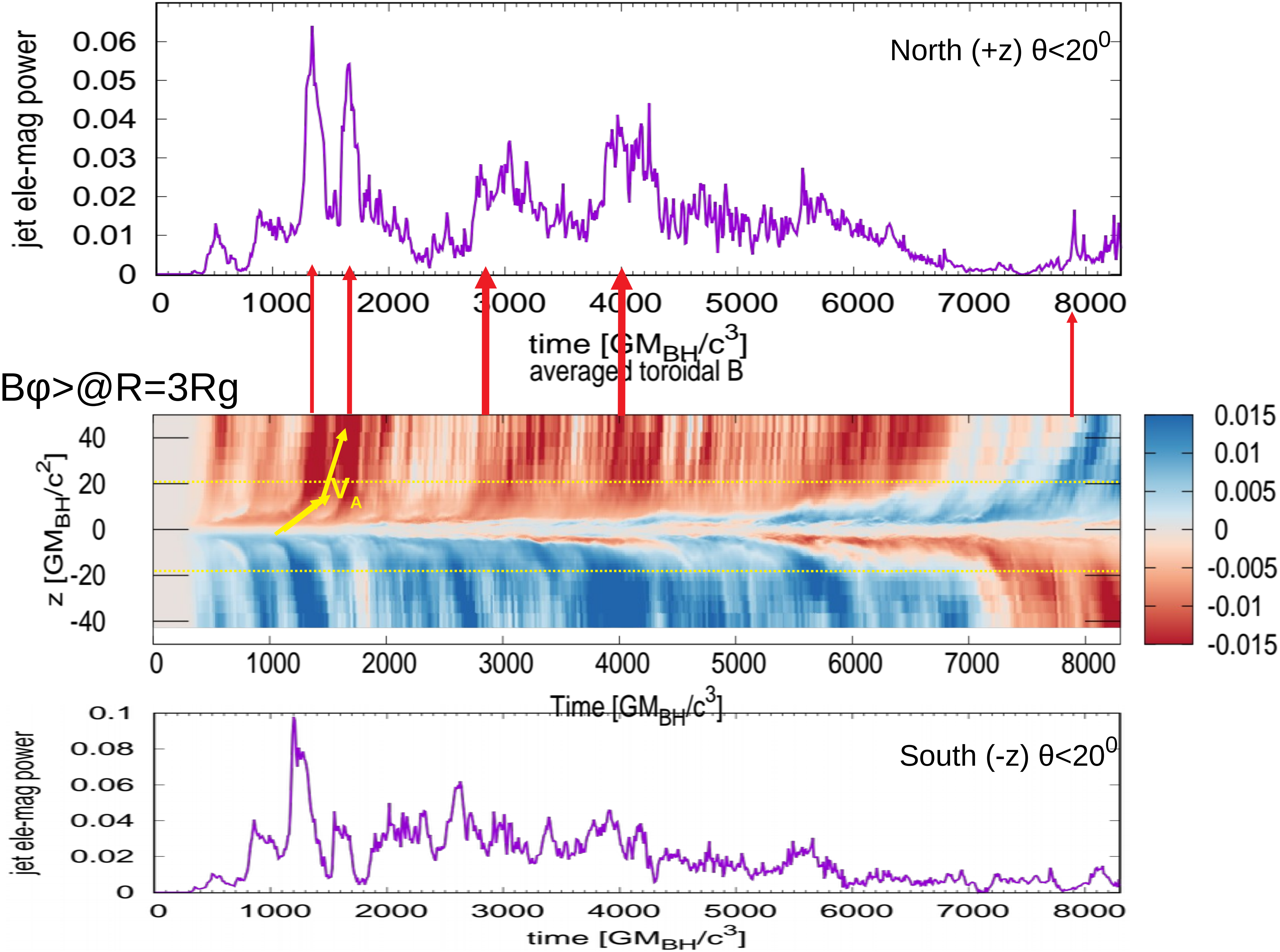
Machida +2013

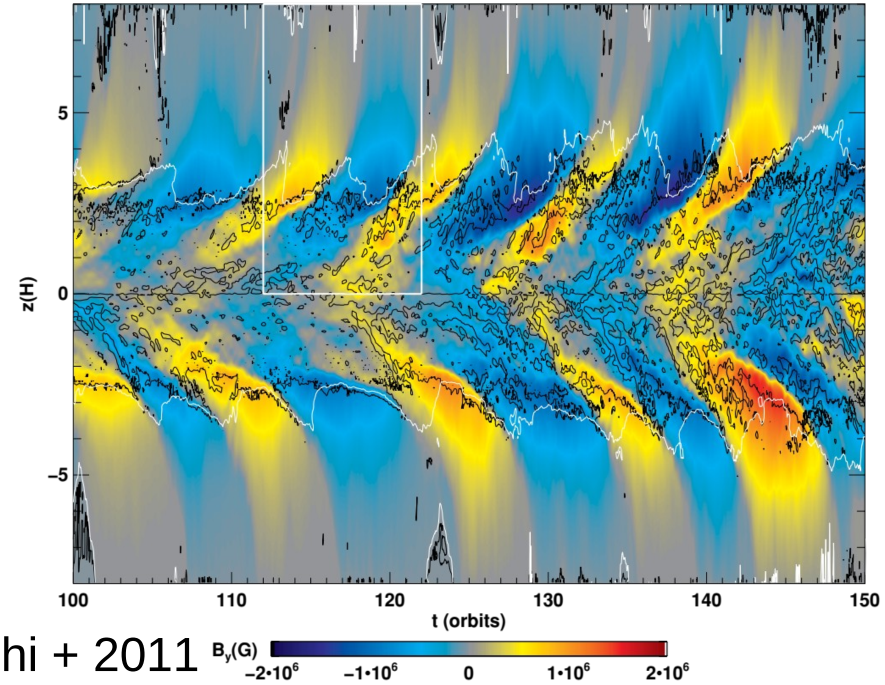

North (+z) θ<20^0
jet ele-mag power
0.06
0.05
0.04
0.03
0.02
0.01
0
0
1000
2000
3000
4000
5000
6000
7000
8000
time [GM_{BH}/c^3]
averaged toroidal B
V_A
z [GM_{BH}/c^2]
40
20
0
-20
-40
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
Time [GM_{BH}/c^3]

<Bφ>@R=3Rg

<Bφ>@R=3Rg

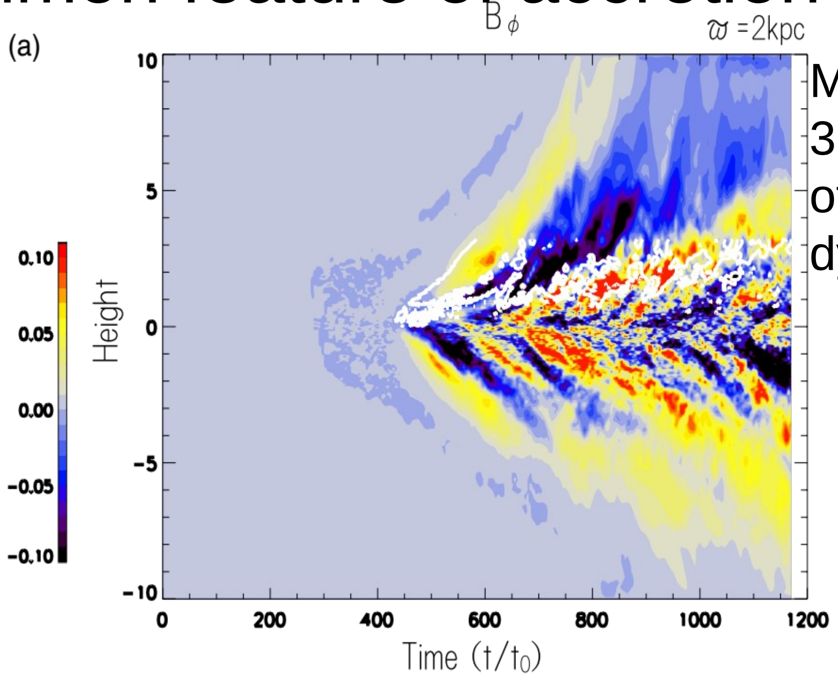

jet ele-mag power
0.06
0.05
0.04
0.03
0.02
0.01
0
North (+z) θ<20⁰
0
1000
2000
3000
4000
5000
6000
7000
8000
time [GMBH/c³]
averaged toroidal B
z [GMBH/c²]
40
20
0
-20
-40
V_A
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
Time [GMBH/c³]
jet ele-mag power
0.1
0.08
0.06
0.04
0.02
0
South (-z) θ<20⁰
time [GMBH/c³]

Butterfly diagram is common feature of accretion disk



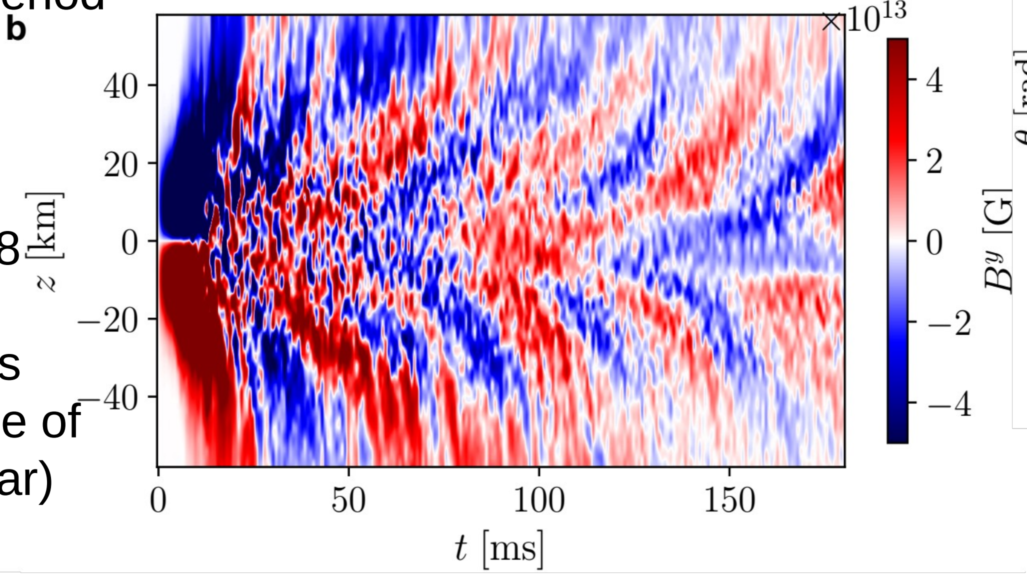
Shi + 2011

Local box sim. Protosteller disk

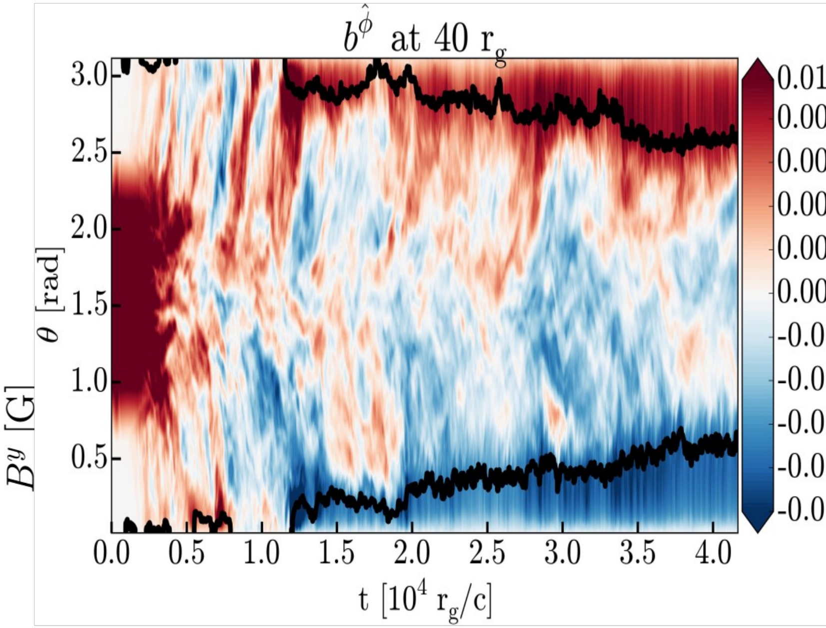


Machida + 2013
3D MHD sim
of galactic
dynamo

Repeat timescale
∼10 orbital period
See also
Suzuki 2009

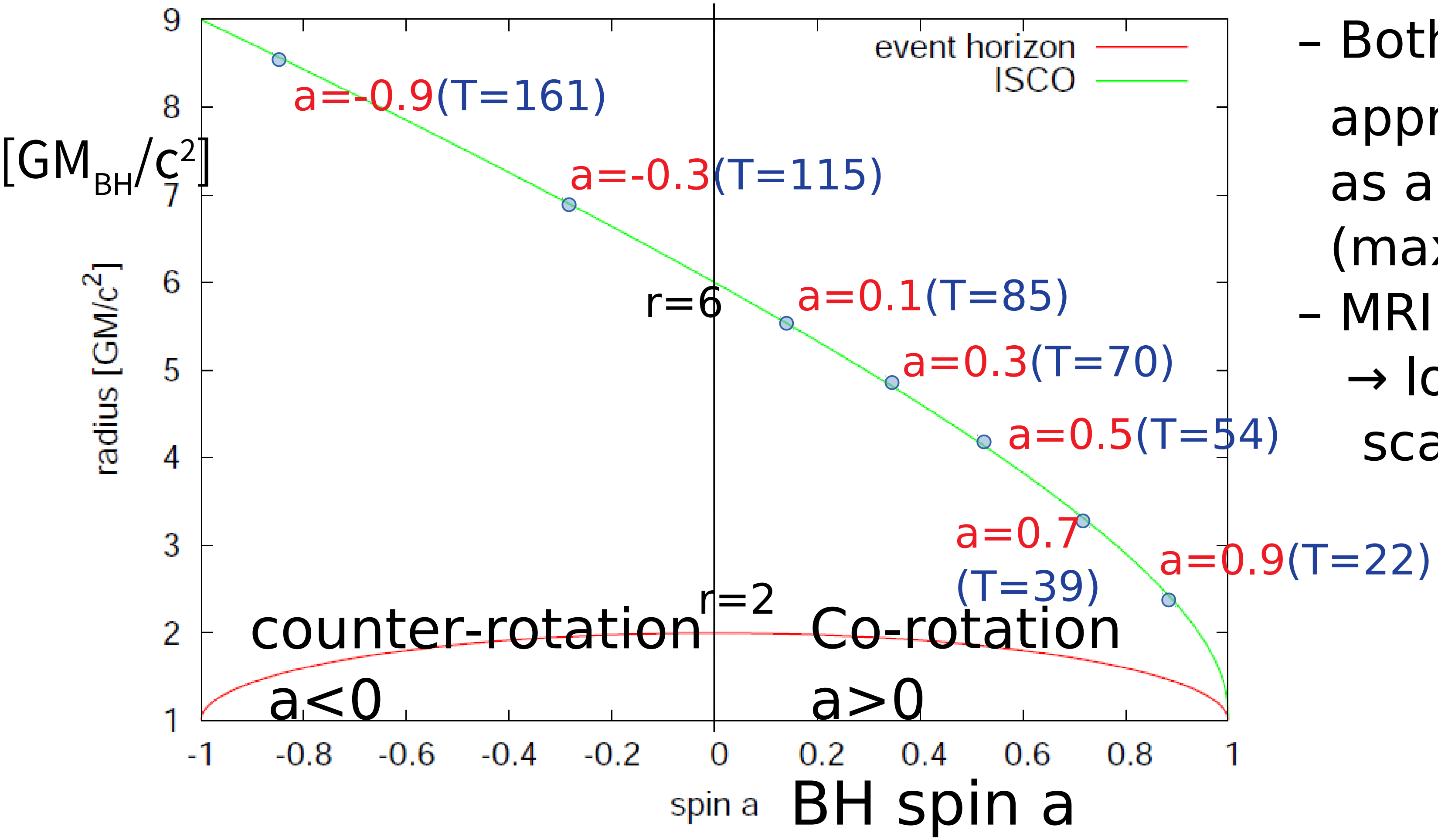


Siegel + 2018
GRMHD
+ ν cooling as
central engine of
GRB(collapsar)



Liska + 2018
GRMHD+AMR

Event horizon / ISO(innermost stable circular orbit)



- Both r_H and r_{ISCO} approaches r=1 as a=> 1 (maximum spin)
- MRI growth etc. → longer time-scales for small a

$$r_\mathrm{H} = 1 + \sqrt{1 - a^2}$$ (g$_{rr}$ =0 @ Boyer-Lindquist)

$$r_\mathrm{ISCO} = 3 + g(a) \mp \sqrt{[3 - f(a)][3 + f(a) + 2g(a)]}$$

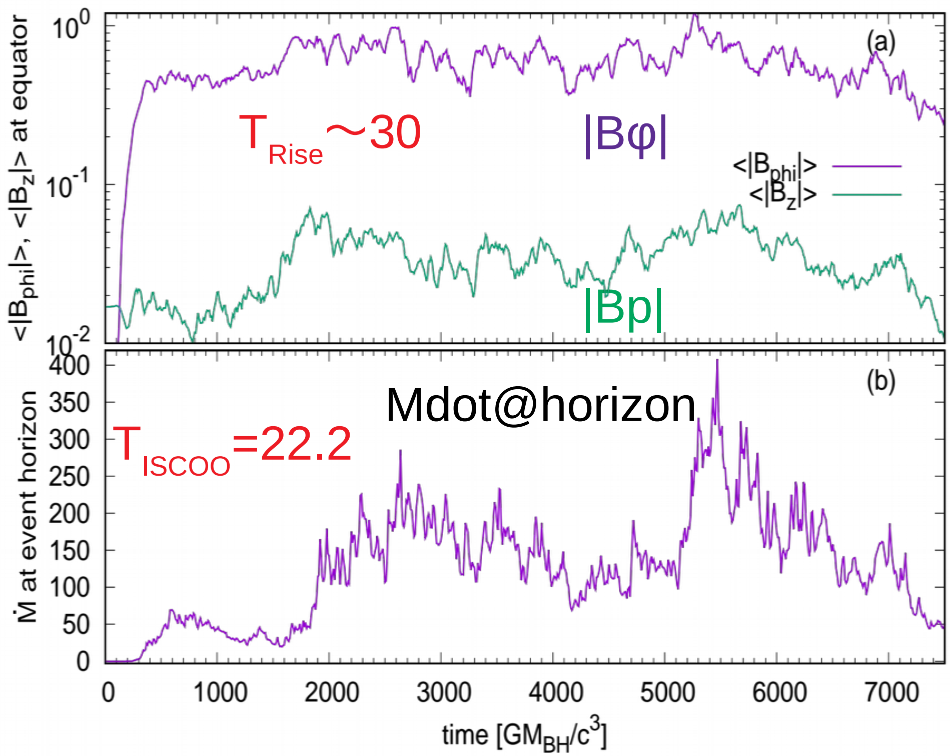
where $f(a) \equiv 1 + (1 - a^2)^{1/3}[(1 + a)^{1/3} + (1 - a)^{1/3}]$

$$g(a) \equiv \sqrt{(3a^2 + f(a)^2)}$$

Bardeen +1972

Kerr Spin parameter (a) dependence

a=0.9



$T_{Rise}\sim 30$

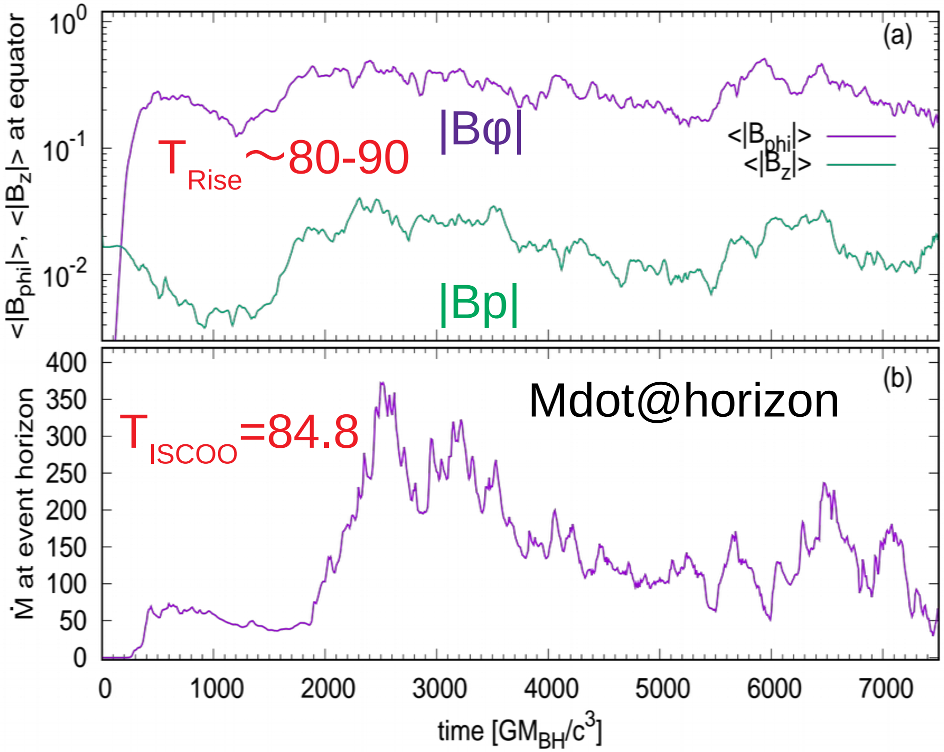
|Bφ|

|Bp|

$T_{ISCOO}=22.2$

Mdot@horizon

a=0.1



$T_{Rise}\sim 80\text{-}90$

|Bφ|

|Bp|

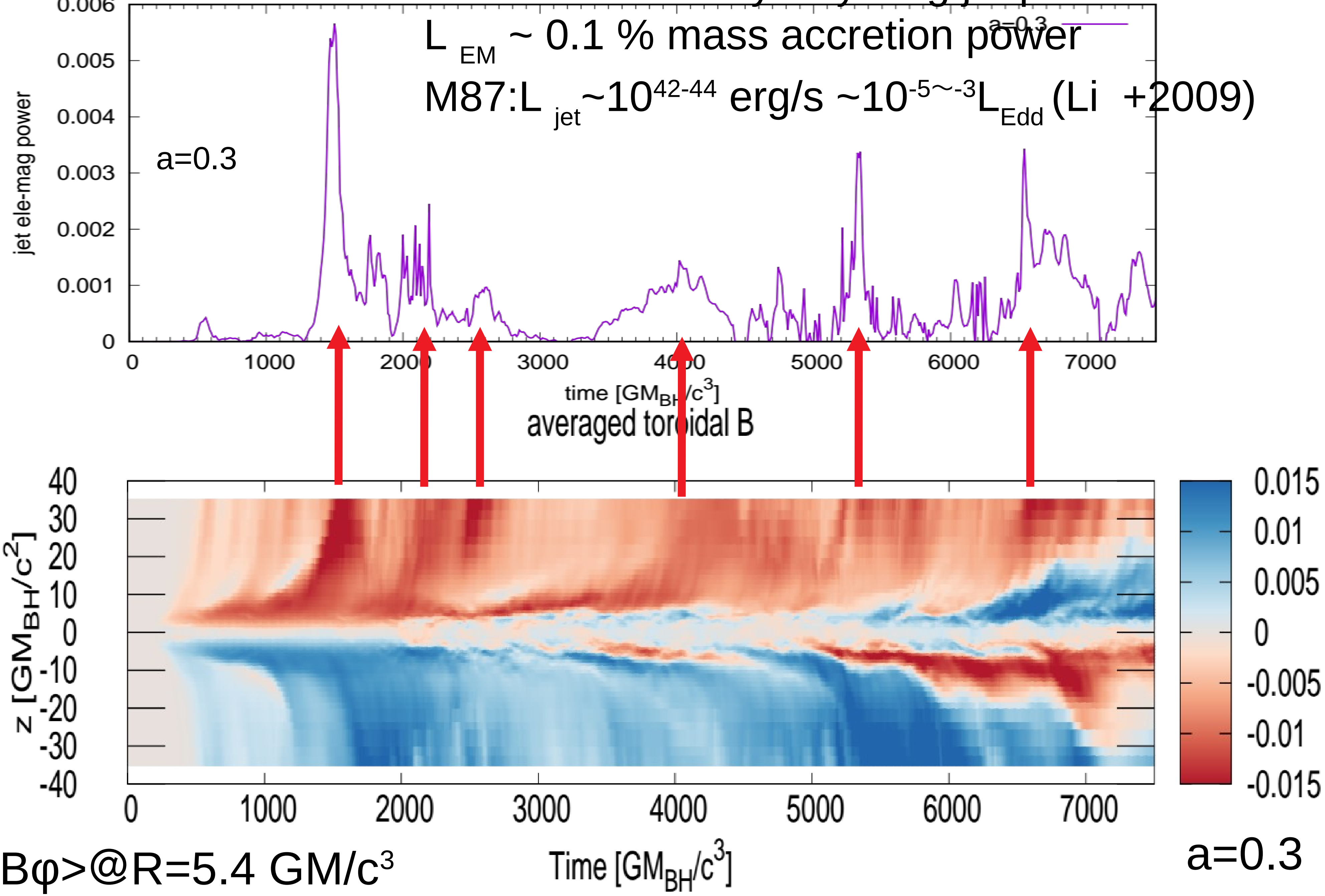
$T_{ISCOO}=84.8$

Mdot@horizon

— Longer timescales for B-filed amplification and mass accretion rate for lower spin a case.

—The timescales are consistent with orbital pereod @ radius = r_{ISCO} + α.

Butterfly diagram & EM jet power



Vert low Efficiency Poynting jet power

L_{EM} ~ 0.1 % mass accretion power

M87: L_{jet} ~10^{42-44} erg/s ~$10^{-5\sim-3} L_{Edd}$ (Li +2009)

<Bφ>@R=5.4 GM/c^3

a=0.3

Conclusion

- Jets are produced from central objects and accretion disks in different scales in the Universe.
- 3D general relativistic magnetohydrodynamic simulations are powerful tool to study the physics of accretion flows onto BH and jets launching mechnism.
- Magnetic filefd amplification via Magneto-Rotational Instability (MRI) is important to understand accretion flows because angular momentum is transferred to the outer region and effieint mass accretion is realized.
- low beta disk ⇔ high beta disk transition is observed. short timevariability not only in the disk but also in jets
- Accretion disk butterfly diagram seems common feature for accretion flows onto any objects.
- For higher BH spin parameter
  - shorter timevariability (MRI growth, repeat cycle)
  - more efficient Poynting jets are observed