Simulations of magnetospheres and accretion discs

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with

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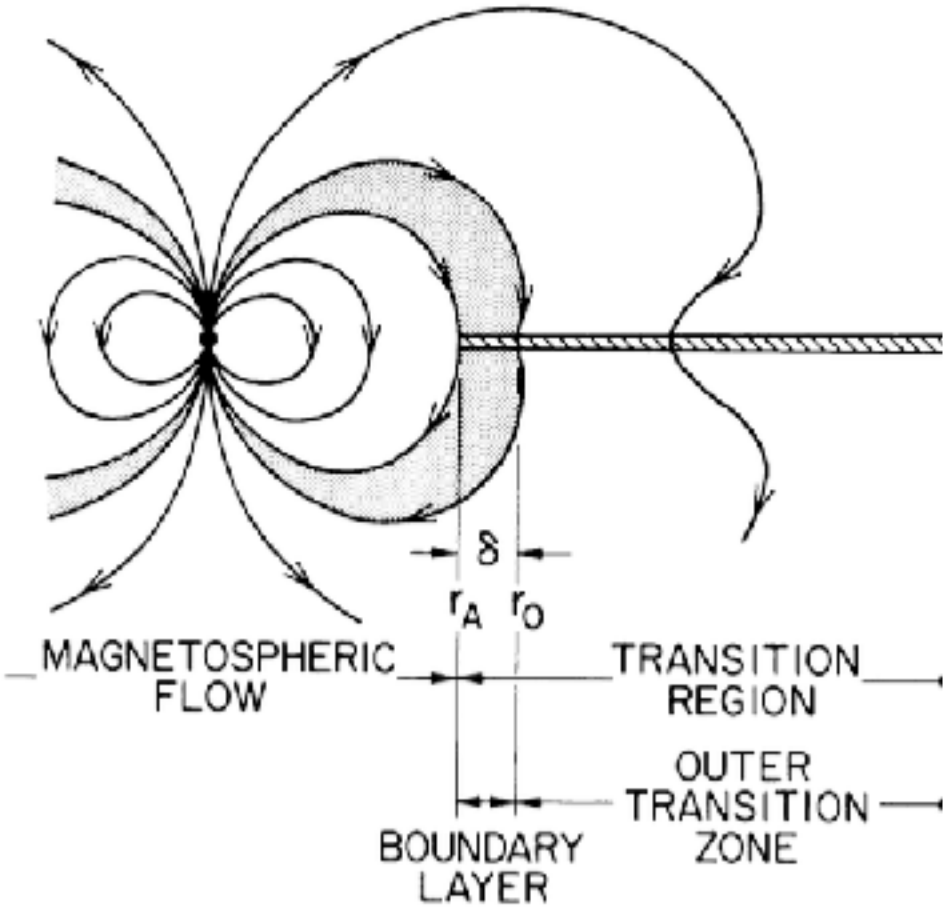
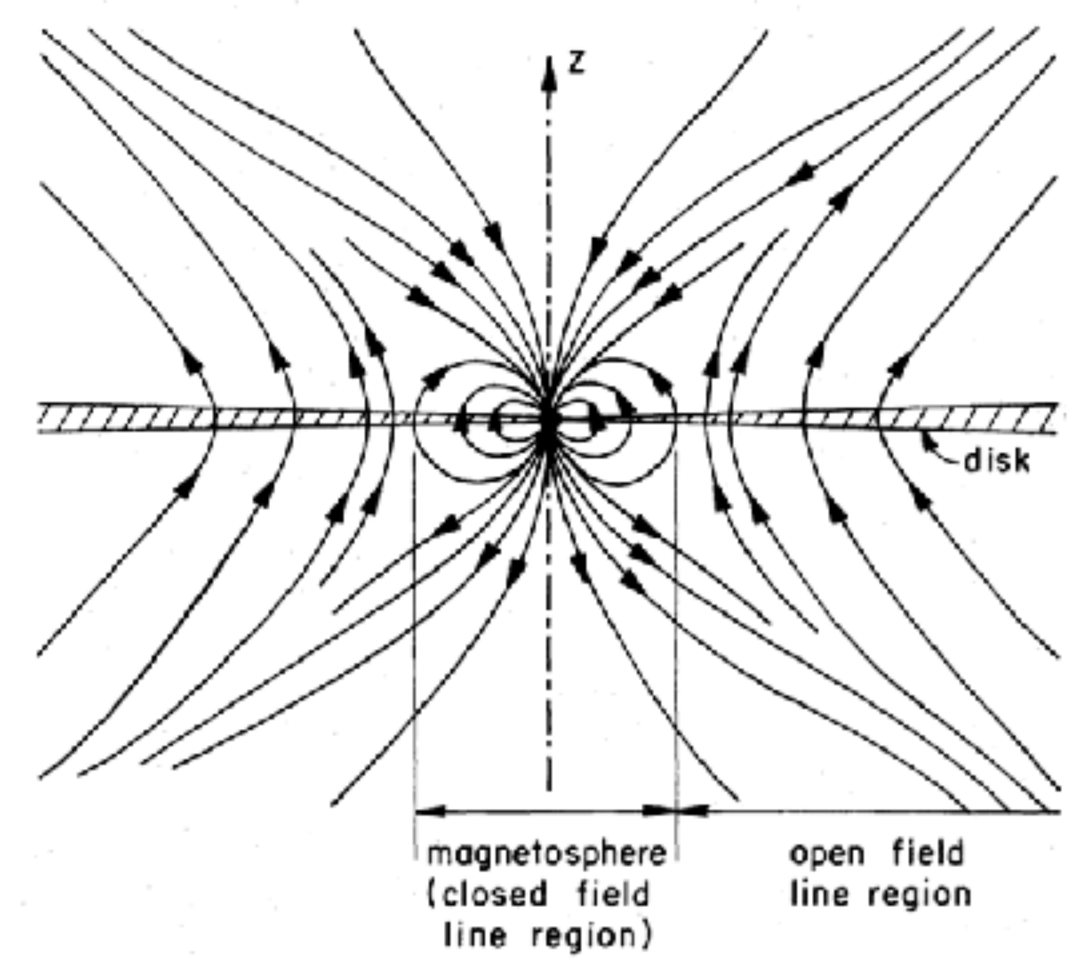
Global magnetospheric geometry

Closed…



Ghosh & Lamb 1978

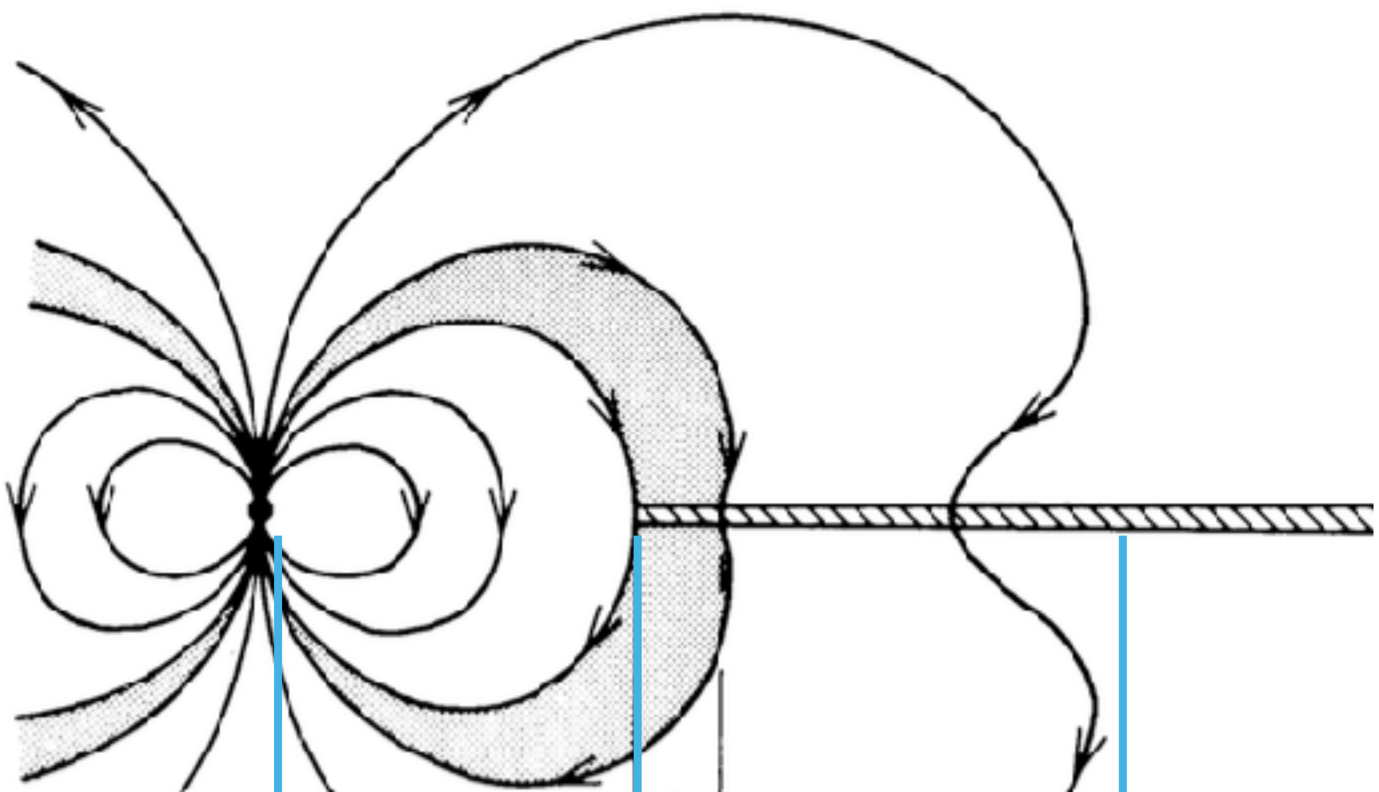
…or open?



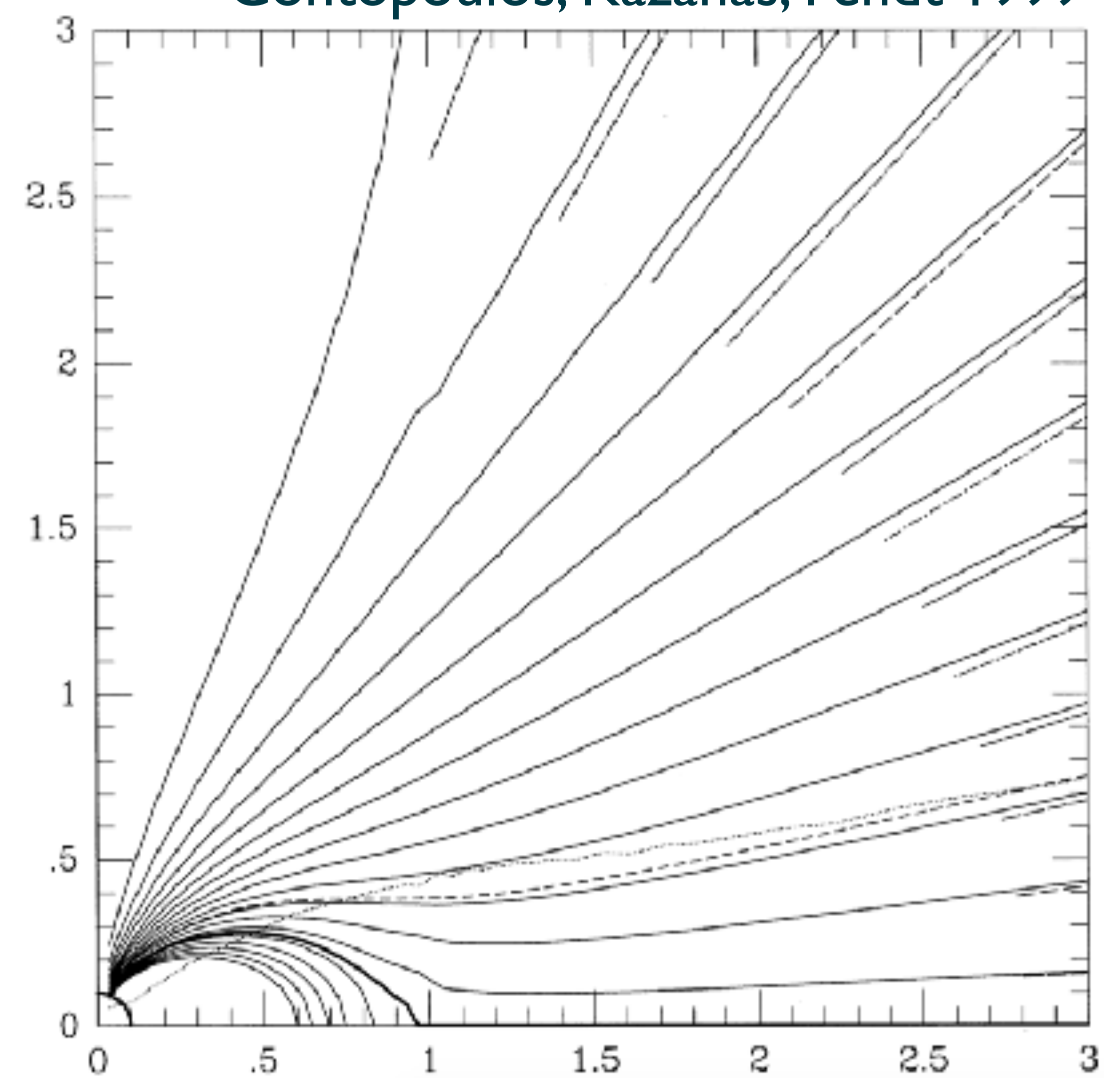
Lovelace, Romanova & Bisnovatyi-Kogan 1995

1. Disc exerts torques on the star via the field lines & vice-versa
2. Radio jet may be driven by the stellar rotation + open magnetic flux

Important radii



Contopoulos, Kazanas, Fendt 1999



r_{star} stellar

r_m magnetospheric

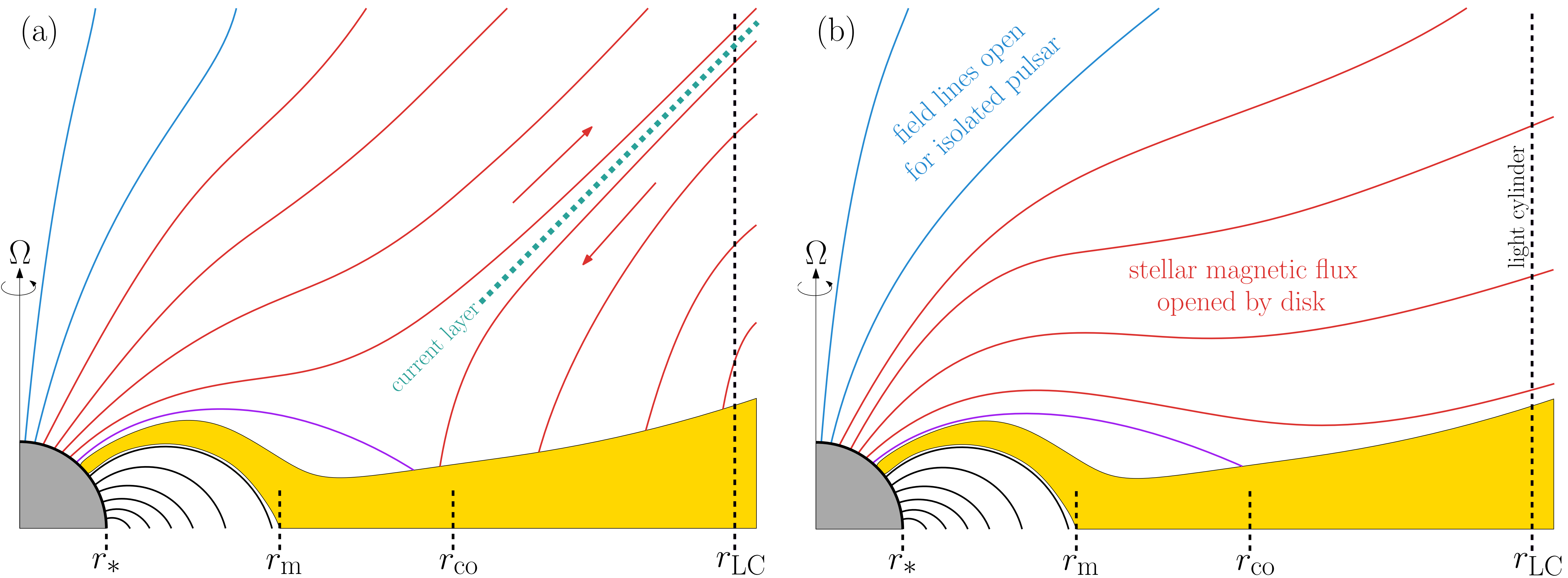
r_{co} corotation

r_{LC} light cylinder

A simple model for NS-powered jets

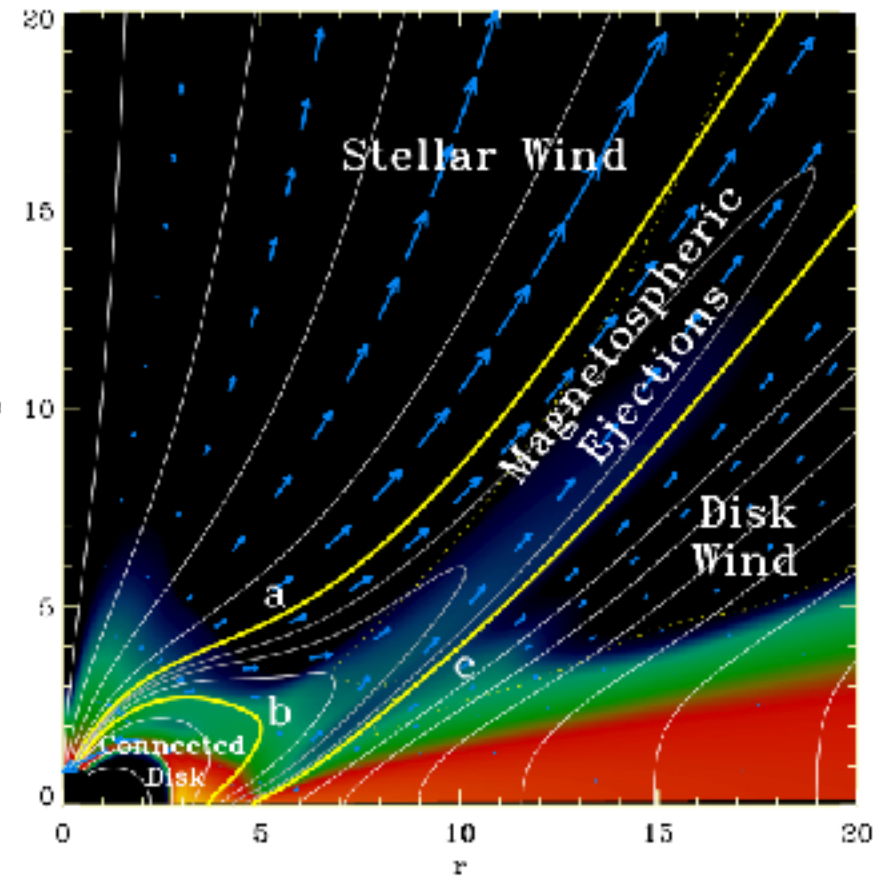
Associate jet power with energy flux
on open field lines

KP, Spitkovsky, Beloborodov 2016

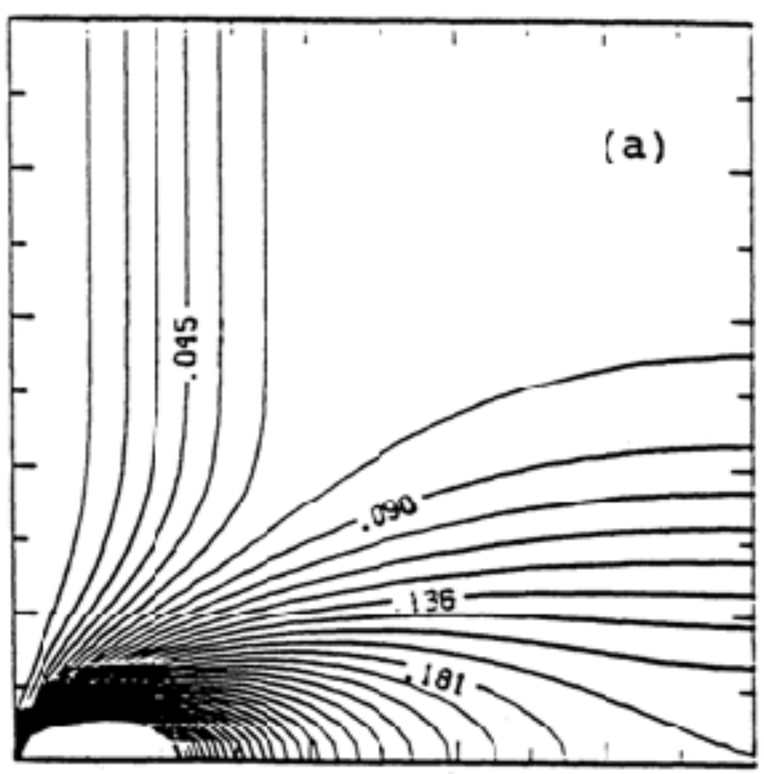


But how much flux is opened? Expect: $\psi_{\rm open} \sim \dfrac{r_{\rm LC}}{r_{\rm m}} \psi_{\rm open,0}$

Relativistic jet — if open flux is collimated



Zanni & Ferreira 2013



Sulkanen & Lovelace 1990

Isolated pulsar:

$$L_0 = -N_0\Omega = \mu^2\frac{\Omega^4}{c^3} \approx \frac{2}{3c}\Omega^2\psi^2_{\mathrm{open},0}$$

Model for open flux: $\psi_{\mathrm{open}} = \zeta\frac{r_{\mathrm{LC}}}{r_{\mathrm{m}}}\psi_{\mathrm{open},0}$

Estimated jet power: $L_{\mathrm{j}} = \zeta^2\left(\frac{r_{\mathrm{LC}}}{r_{\mathrm{m}}}\right)^2 L_0$

(Can estimate torques *N* in the same way)

Jet power estimate

Estimated jet power: $L_{\rm j} = \zeta^2 \left(\frac{r_{\rm LC}}{r_{\rm m}}\right)^2 L_0$

$$L_{\rm j} = 1.59 \times 10^{36} \left(\frac{\zeta}{\xi}\right)^2 \left(\frac{\nu}{500\,{\rm Hz}}\right)^2 \left(\frac{\mu}{10^{26}\,{\rm G\,cm^3}}\right)^{6/7}$$
$$\times \left(\frac{M}{1.4\,M_\odot}\right)^{6/7} \left(\frac{\dot{M}}{\dot{M}_{\rm Edd,\odot}}\right)^{4/7} {\rm erg\,s^{-1}}$$

where disc truncation radius: $r_{\rm m} = \xi r_{\rm A}$

is related to classic Alfven radius: $r_{\rm A} = \left(\frac{\mu^4}{2GM\dot{M}^2}\right)^{1/7}$

KP, Spitkovsky, Beloborodov 2016

Observed jet powers

Sco X-1, Cir X-1 — $L_{\rm j} > 10^{35}$ erg/s

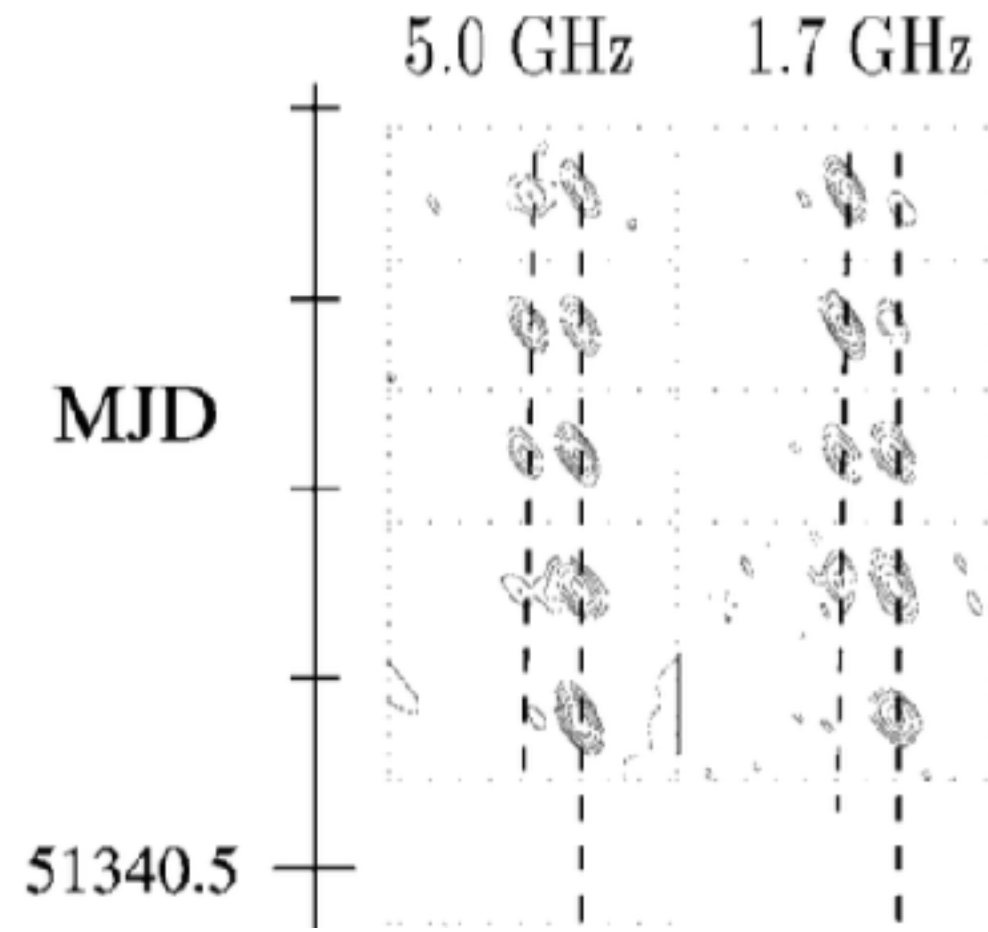
Fomalont+ 2001, Fender+ 2004

Model: $L_{\rm j} = 4.6 \times 10^{35} (\zeta/\xi)^2 \, {\rm erg \, s^{-1}}$

for $B_* = 10^8 \, {\rm G}$ $\quad \nu = 300 \ {\rm Hz}$

$\dot{M} = 0.5 \, \dot{M}_{\rm Edd}$

Sco X-1



Fomalont+ 2001

Ho II X-1 — $L_{\rm j} \sim 10^{39}$ erg/s Cseh+ 2014

For $B = 10^{13}$ G, $\nu = 10$ Hz: $L_0 \sim 6 \times 10^{37}$ erg s^{-1}

$$\xi = 0.3, \quad \dot{M} = 100 \dot{M}_{\rm Edd} \quad \longrightarrow \quad L_{\rm j} = 1.5 \times 10^{39} \, {\rm erg \, s^{-1}}$$

NS jet for short-GRB from binary mergers?

Inferred jet power from GW170817 ~ 10^{49}-10^{50} erg/s

Simple jet model gives:

$$L_{\rm jet} \sim 10^{52} \left(\frac{B_*}{10^{15}\,{\rm G}}\right)^{6/7} \left(\frac{\dot{M}}{{\rm M}_\odot\,{\rm s}^{-1}}\right)^{4/7} \left(\frac{\nu}{\rm kHz}\right)^{2} {\rm erg\,s^{-1}}$$

KP & Tchekhovskoy 2017

Soft State Jet Quenching

Black hole binaries: jets are shut off in the bright, thermal-disc state

May explain why see soft state quenching in some NS binaries

e.g. Aql X-1 Tudose+ 2009, Miller-Jones+ 2010

1RXS J180408 Baglio+ 2016

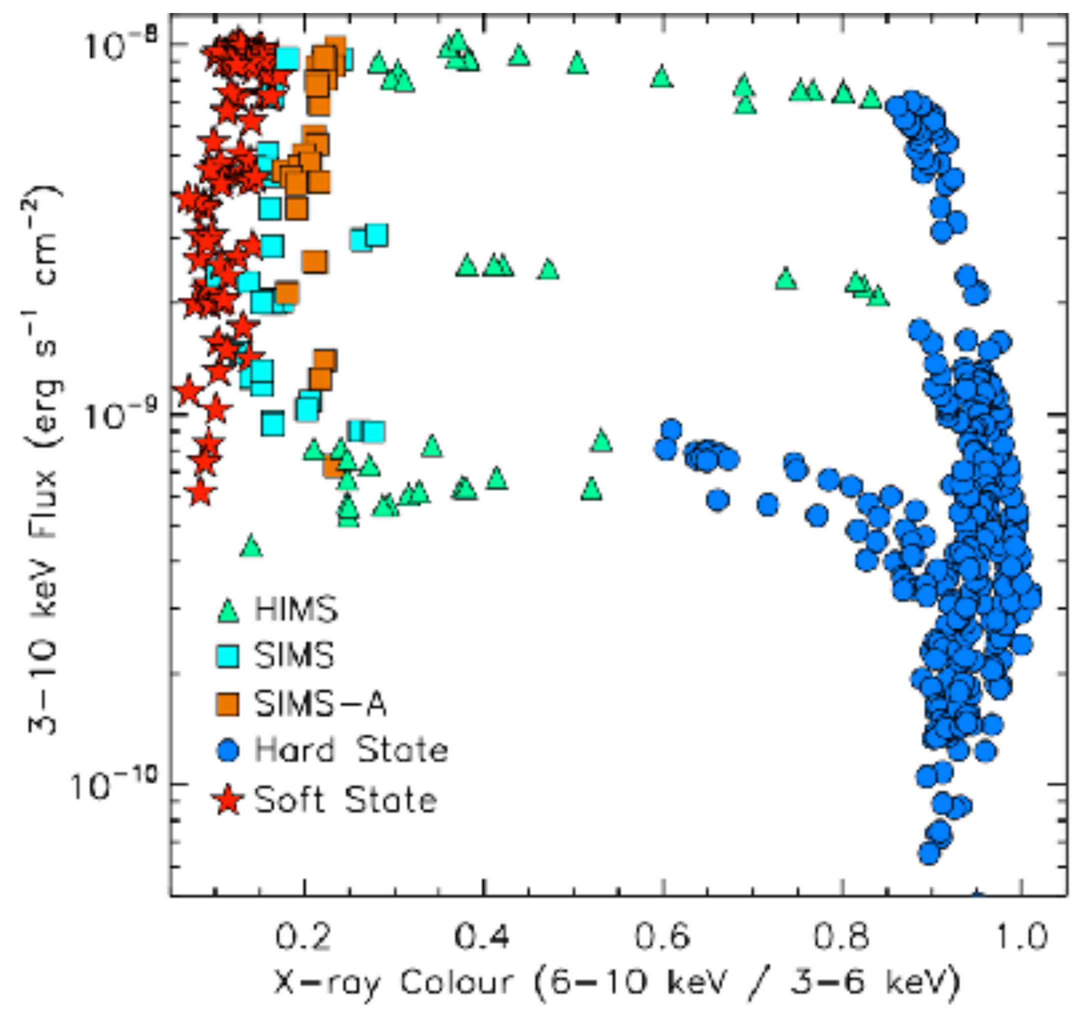
but not others (see Migliari & Fender 2006)

e.g. 4U 1820 Diaz Trigo+ 2017

critical μ for $r_{\rm m} \rightarrow r_*$ at $\dot{M}_{\rm Edd}$

$$\mu_{\rm crit} \sim {\rm few} \times 10^{26}\ {\rm G} \longrightarrow \boldsymbol{B}_* \sim 10^8\,{\rm G}$$

Black hole GX339-4

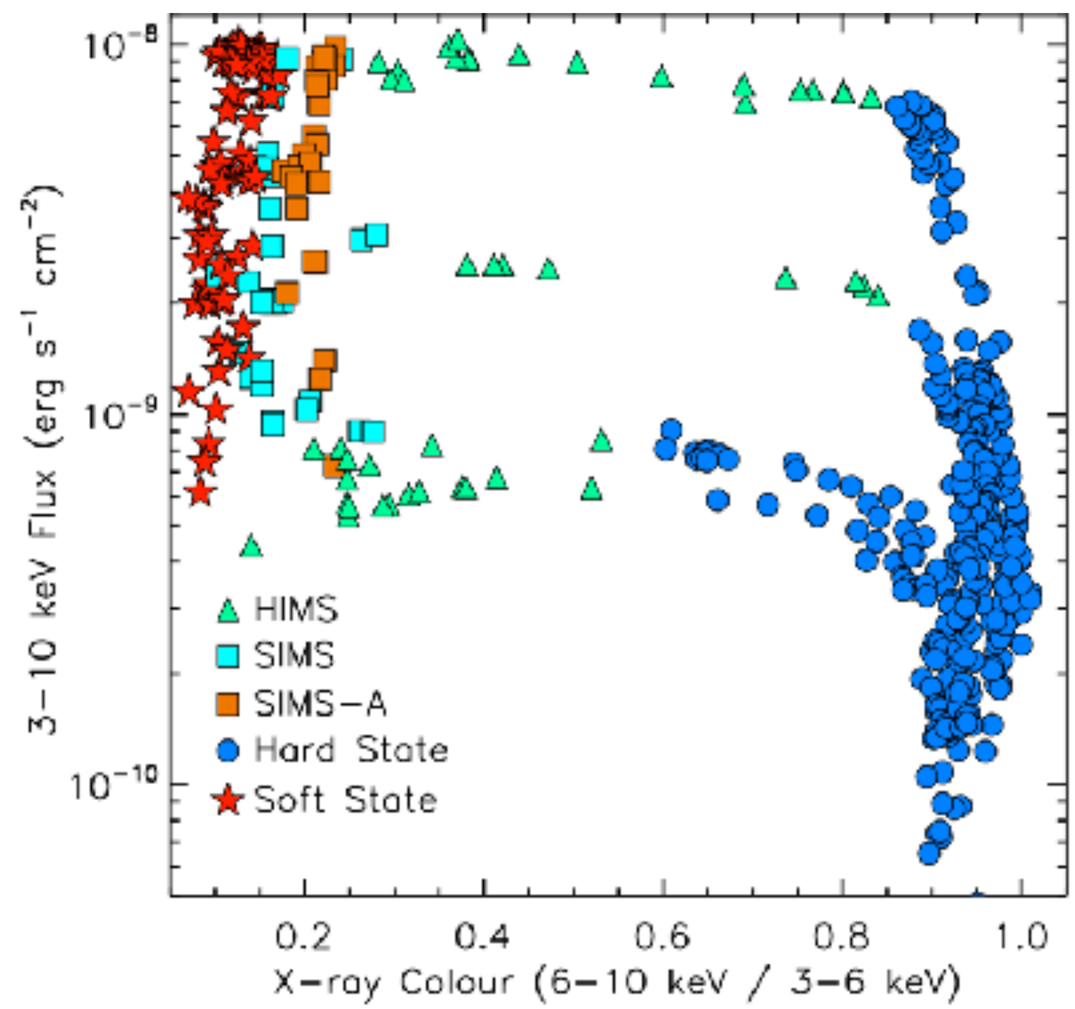


Plant+ 2014

Soft State Jet Quenching

Black hole binaries: jets are shut off in the bright, thermal-disc state

Black hole GX339-4



Plant+ 2014

May explain why see soft state quenching in some NS binaries

e.g. Aql X-1 Tudose+ 2009, Miller-Jones+ 2010

1RXS J180408 Baglio+ 2016; see poster S4.7

but not others (see Migliari & Fender 2006)

e.g. 4U 1820 Diaz Trigo+ 2017

→ critical μ for $r_m \sim r_*$ at $\dot{M}_{Edd}$

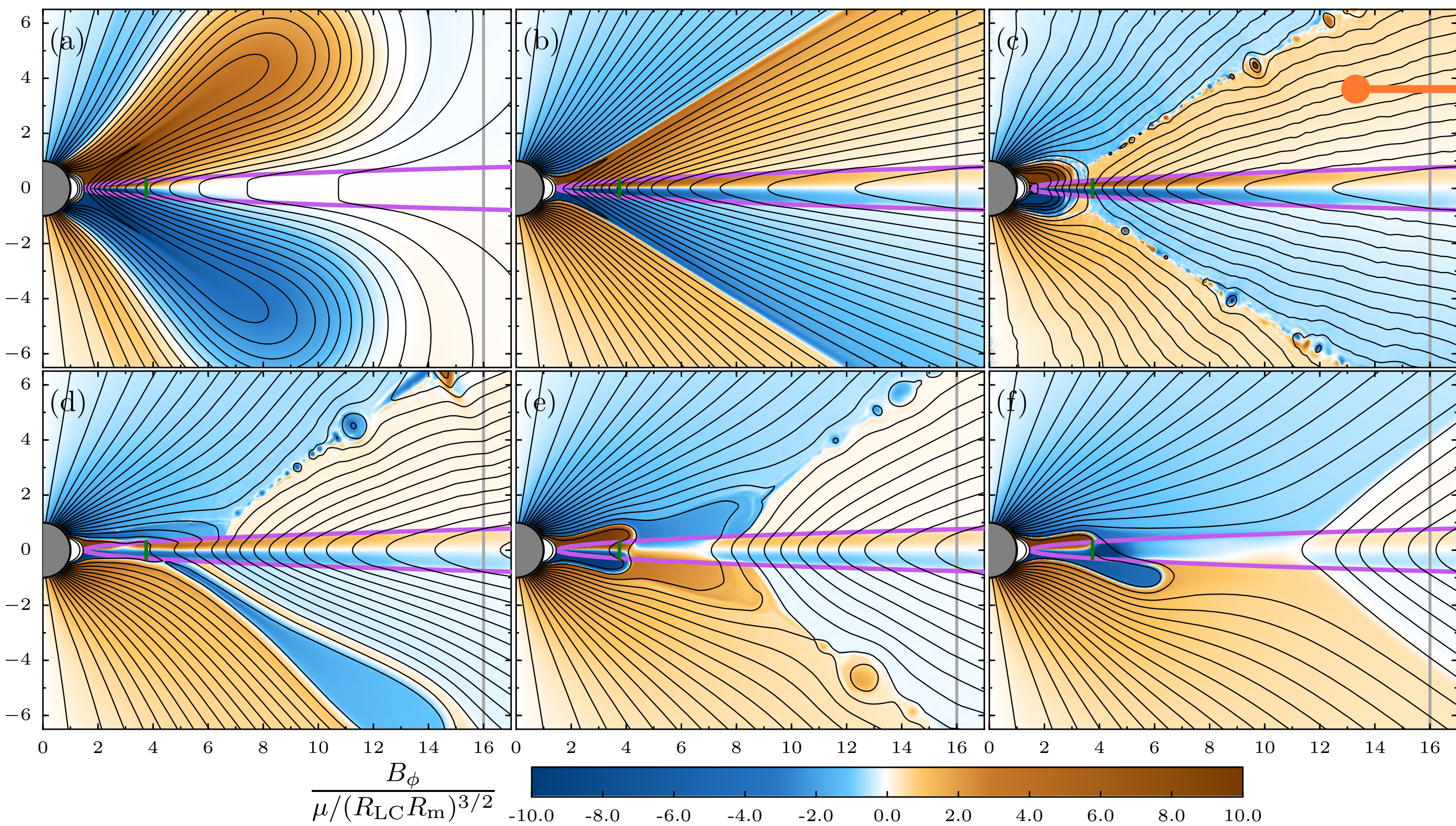
$\mu_{crit} \sim$ few $\times 10^{26}$ G $\longrightarrow$ $B_* \sim 10^8$ G

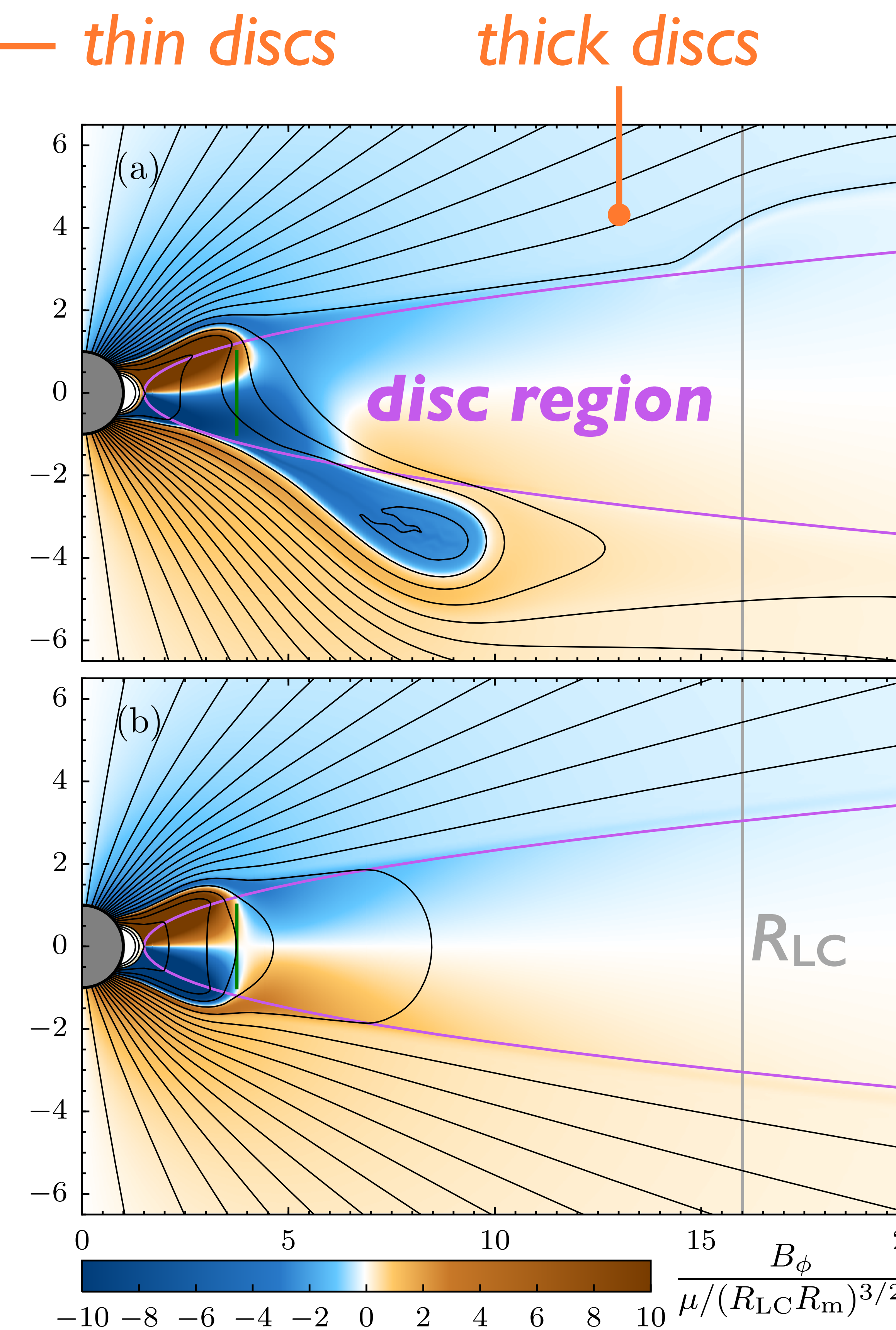
Idea ~ opposite to Massi & Kaufman-Bernado 2008

↓

they predict jet when $R_m < r_{star}$

Relativistic magnetosphere + disc simulations





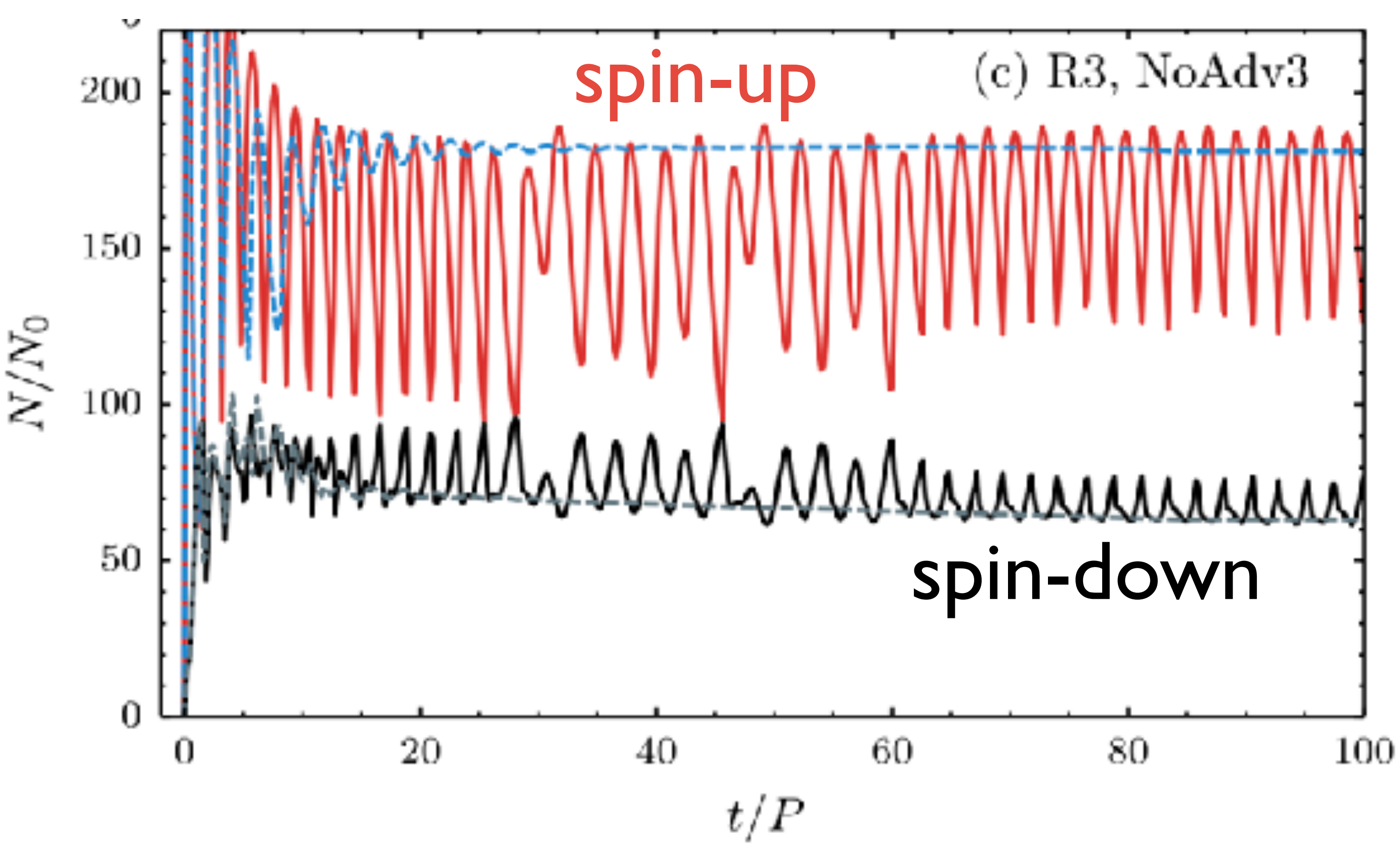
Relativistic force-free magnetosphere
+ imposed/kinematic alpha-disc

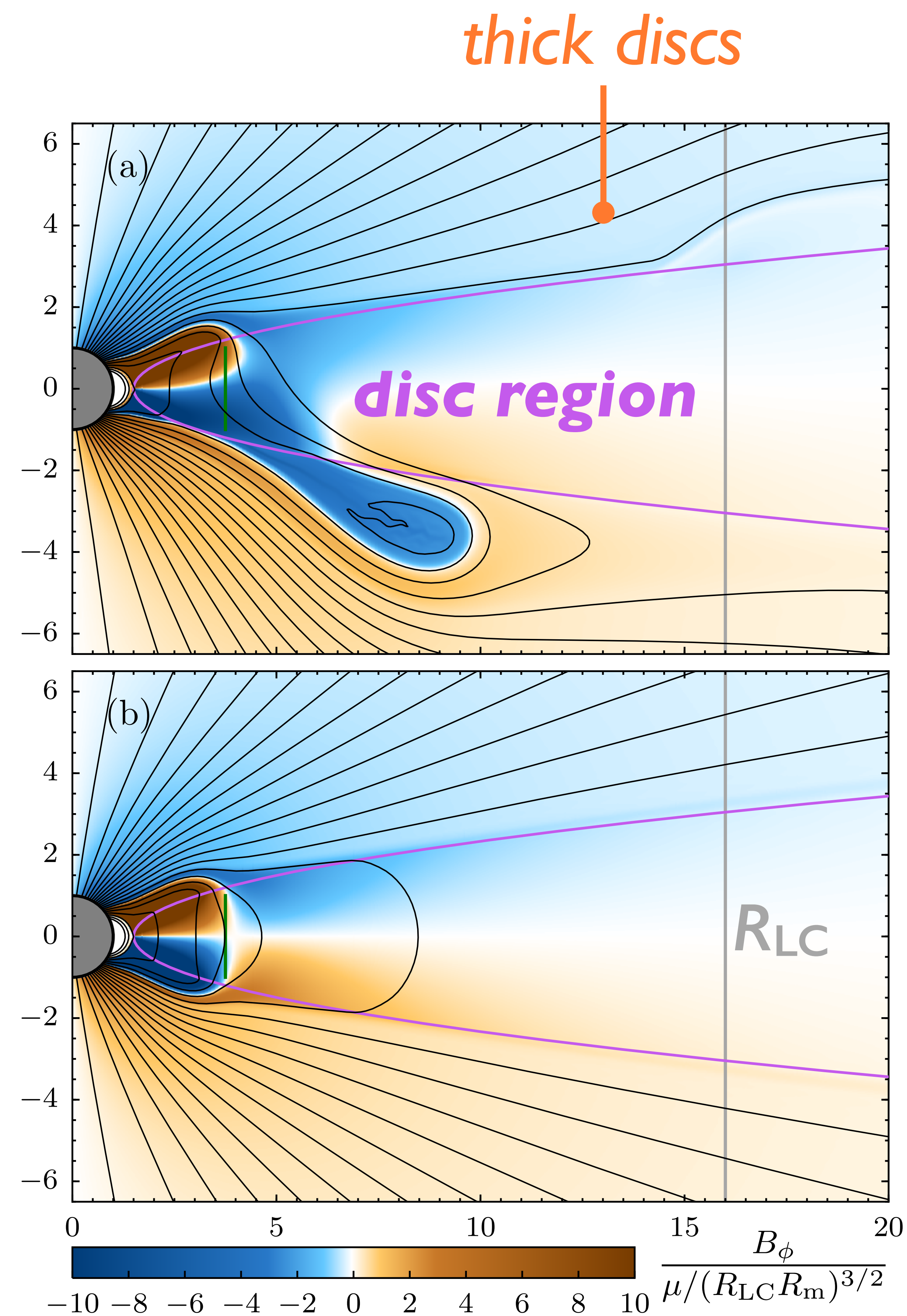
KP, Spitkovsky, Beloborodov 2017

PHAEDRA code: KP, Beloborodov, Hui 2012

Relativistic magnetosphere + disc simulations

Stellar torques in units of isolated-pulsar torque





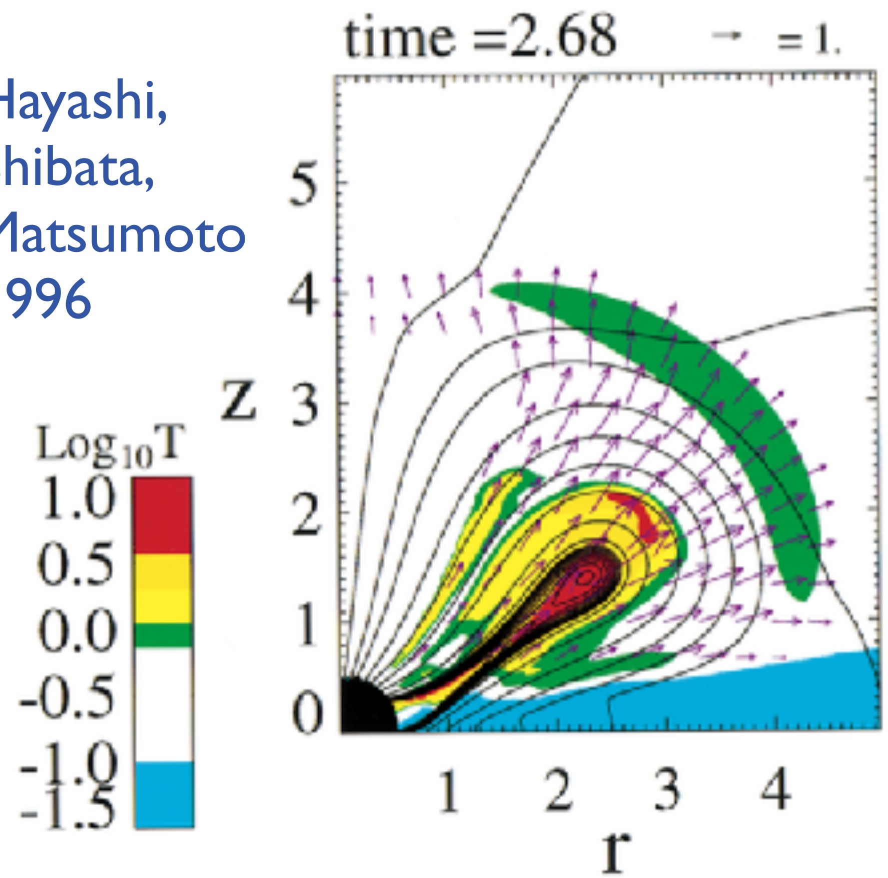
KP, Spitkovsky, Beloborodov 2017

PHAEDRA code: KP, Beloborodov, Hui 2012

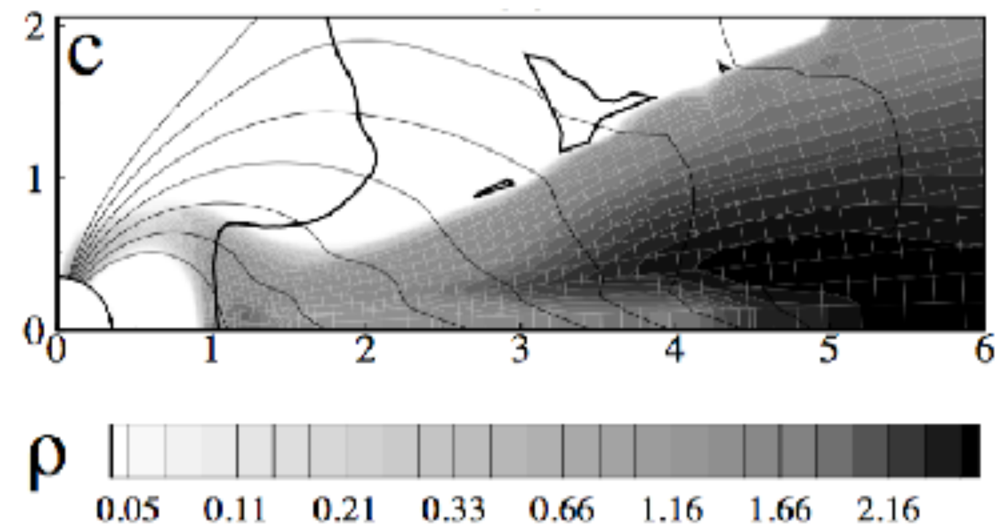
Non-relativistic MHD simulations

opening + reconnection: flaring

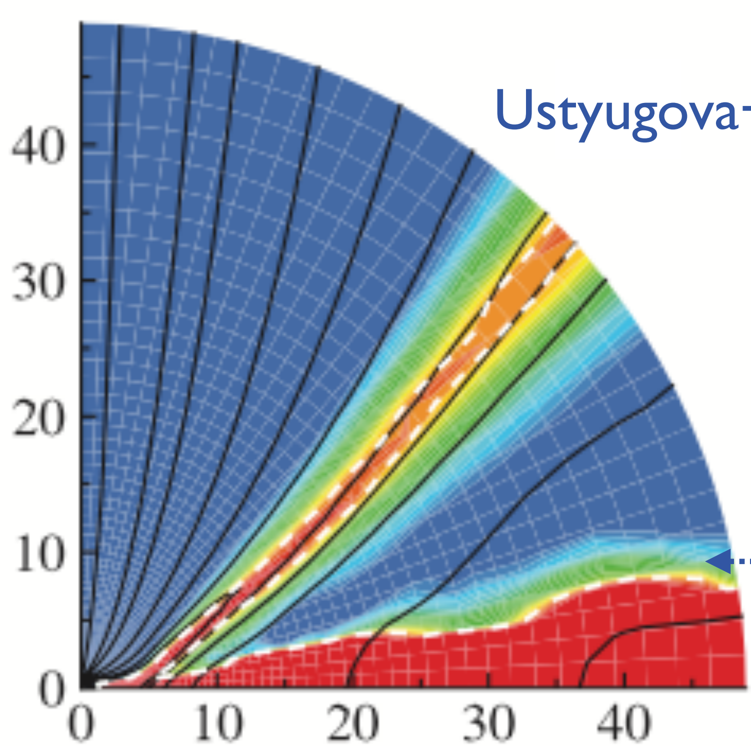
Hayashi, Shibata, Matsumoto 1996



funnel flows & accretion torque



Romanova+ 2002

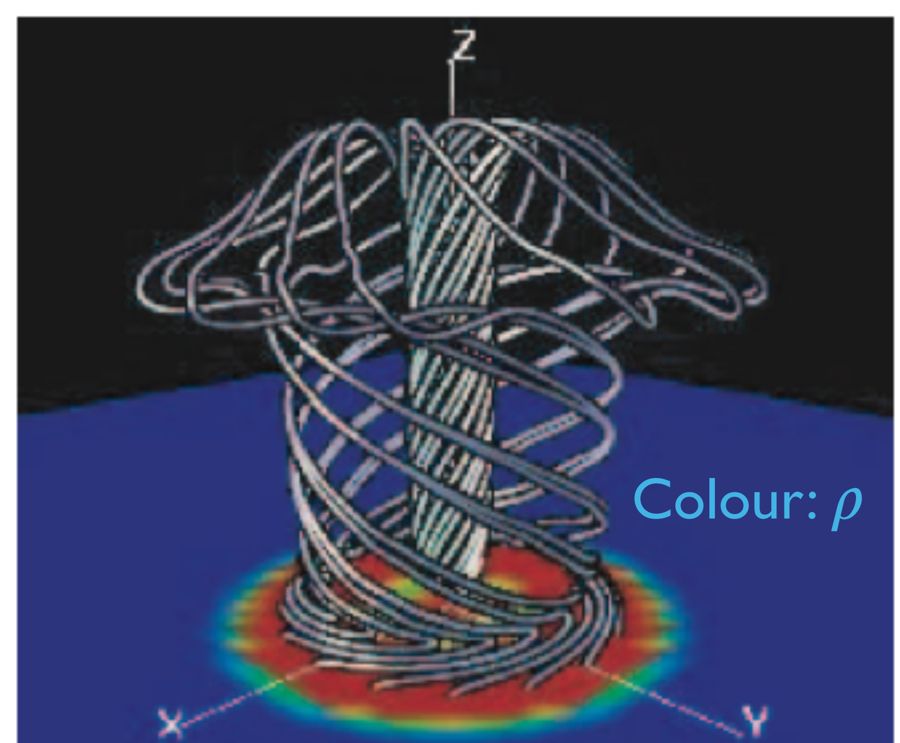


Ustyugova+ 2006

axial magnetised jet

β = 1 contour

Colour: plasma β



Colour: ρ

Kato, Hayashi, Matsumoto 2004

Self-consistent disc physics + relativity

Targets

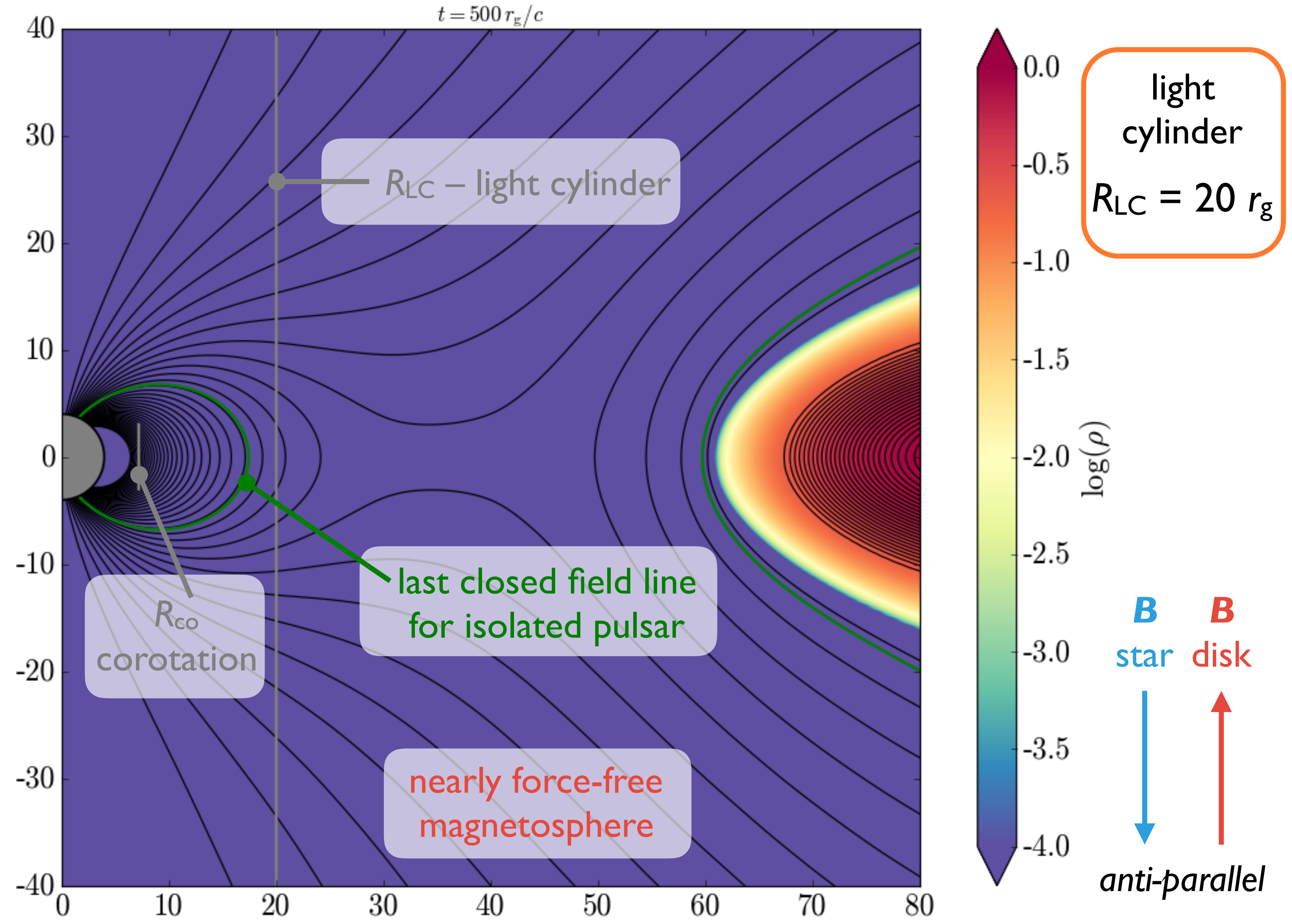
1. Evolve the coupled disc–magnetosphere system self-consistently
2. Accreting material initially entirely outside light cylinder
3. General relativity (fixed spacetime) — Kerr metric
4. Very high magnetization in nearly force-free magnetosphere

GRMHD simulations with HARM code

Gammie, McKinney, Toth 2003, Noble + 2006

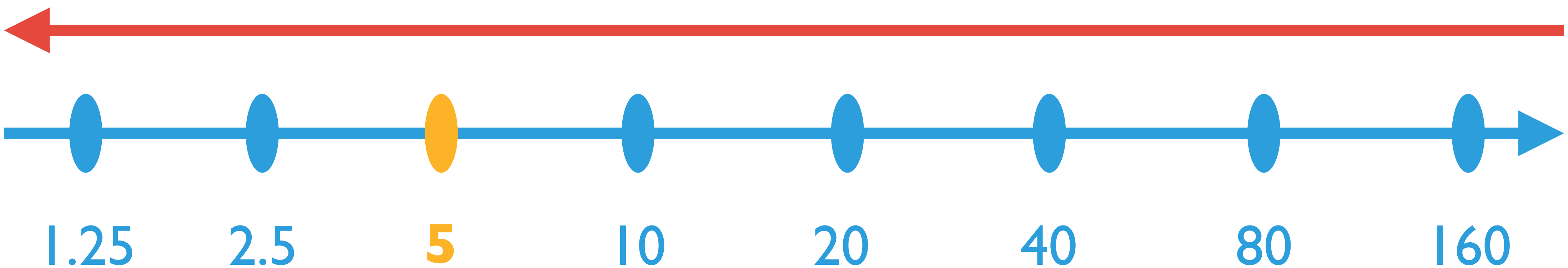
Simulation properties

1. Total-energy conserving — i.e. include shock heating
2. $\gamma = 4/3$ EOS — suitable for radiation-dominated flows
3. Large-scale poloidal magnetic flux in accretion flow


$t = 500\, r_g/c$
R_{LC} – light cylinder
R_{co}
corotation
last closed field line
for isolated pulsar
nearly force-free
magnetosphere
log(ρ)
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
40
30
20
10
0
-10
-20
-30
-40
0
10
20
30
40
50
60
70
80
light
cylinder
R_{LC} = 20 r_g
$\boldsymbol{B}$
star
$\boldsymbol{B}$
disk
anti-parallel

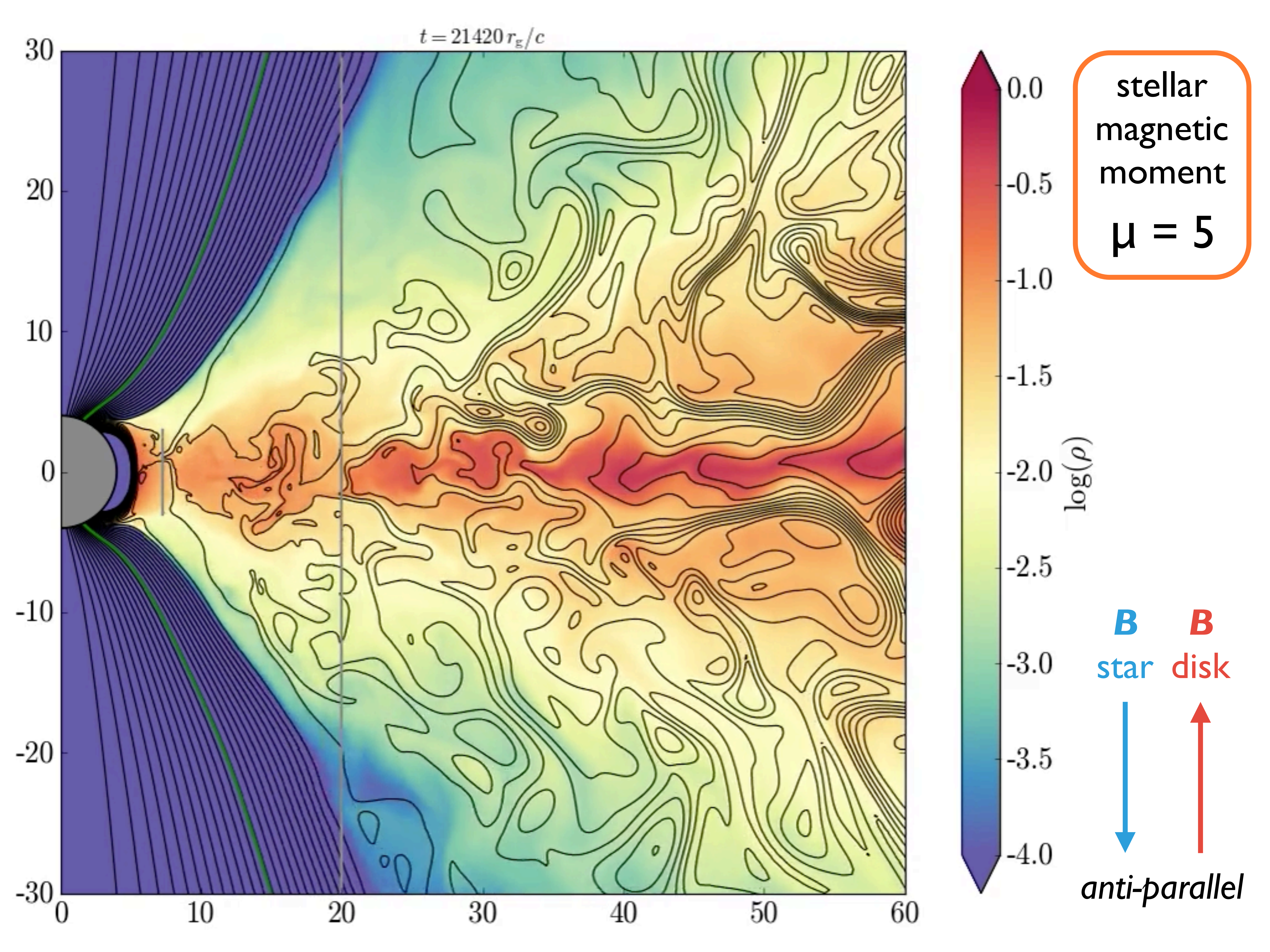
effective mass accretion rate

$$\dot{M} \sim \mu^{-2}$$



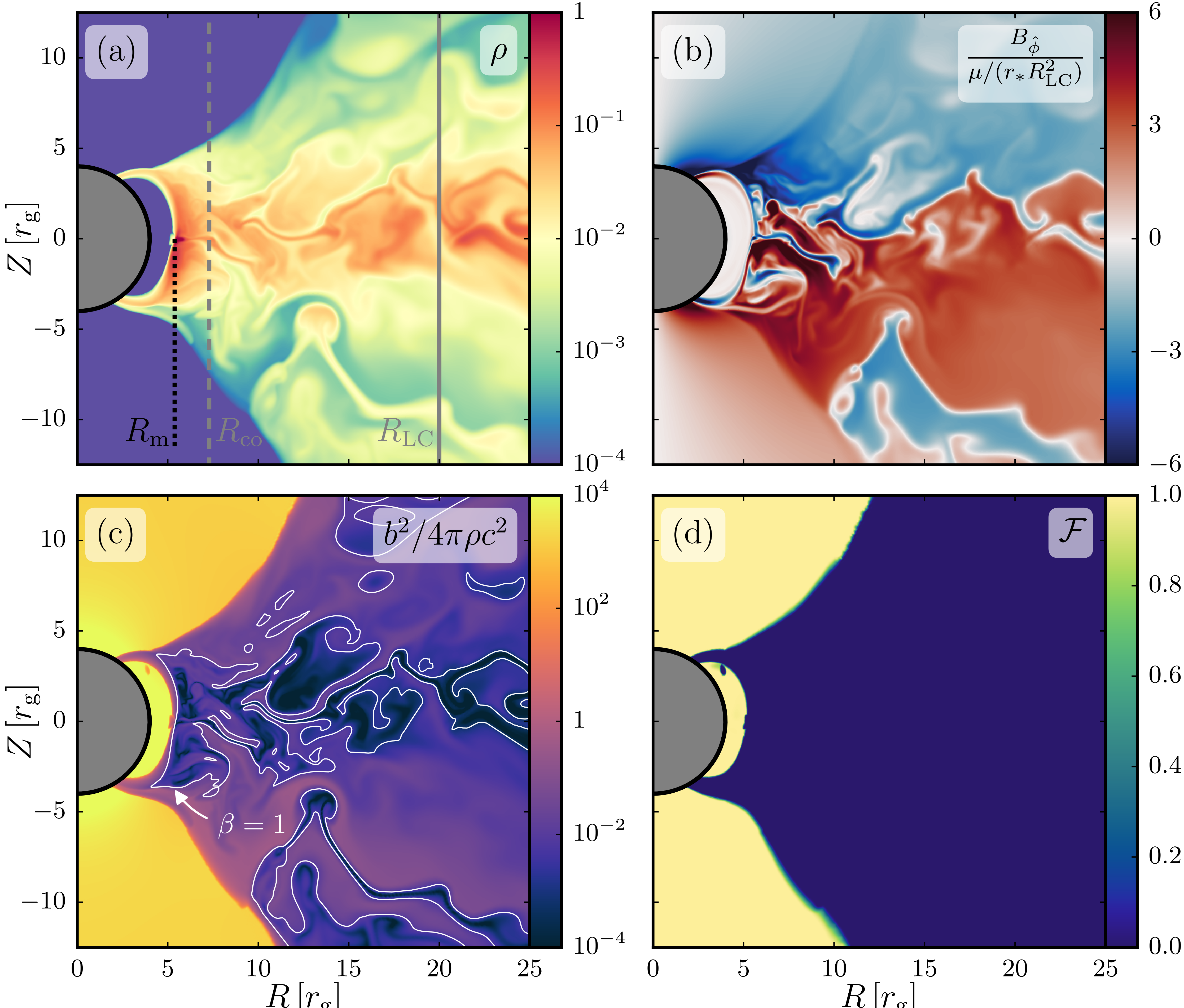
μ

stellar magnetic moment



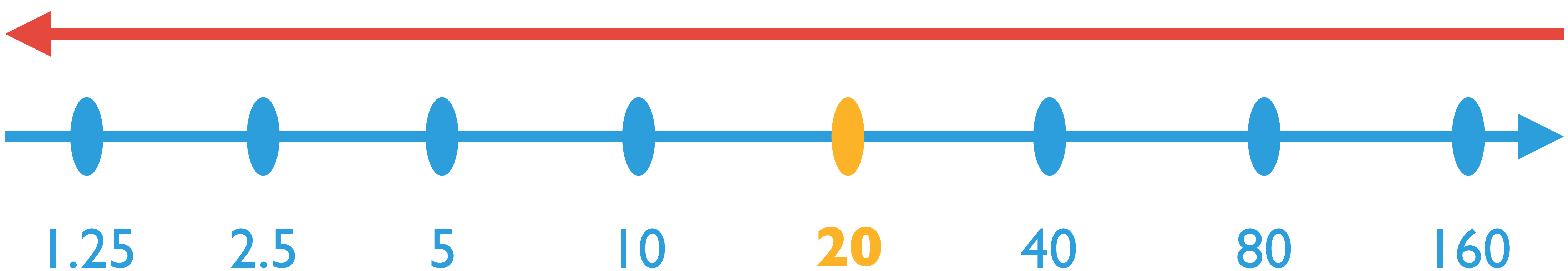
$t = 21420\, r_g/c$
30
20
10
0
-10
-20
-30
0
10
20
30
40
50
60
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
$\log(\rho)$
stellar magnetic moment
μ = 5
B star
B disk
anti-parallel

KP & Tchekhovskoy 2017



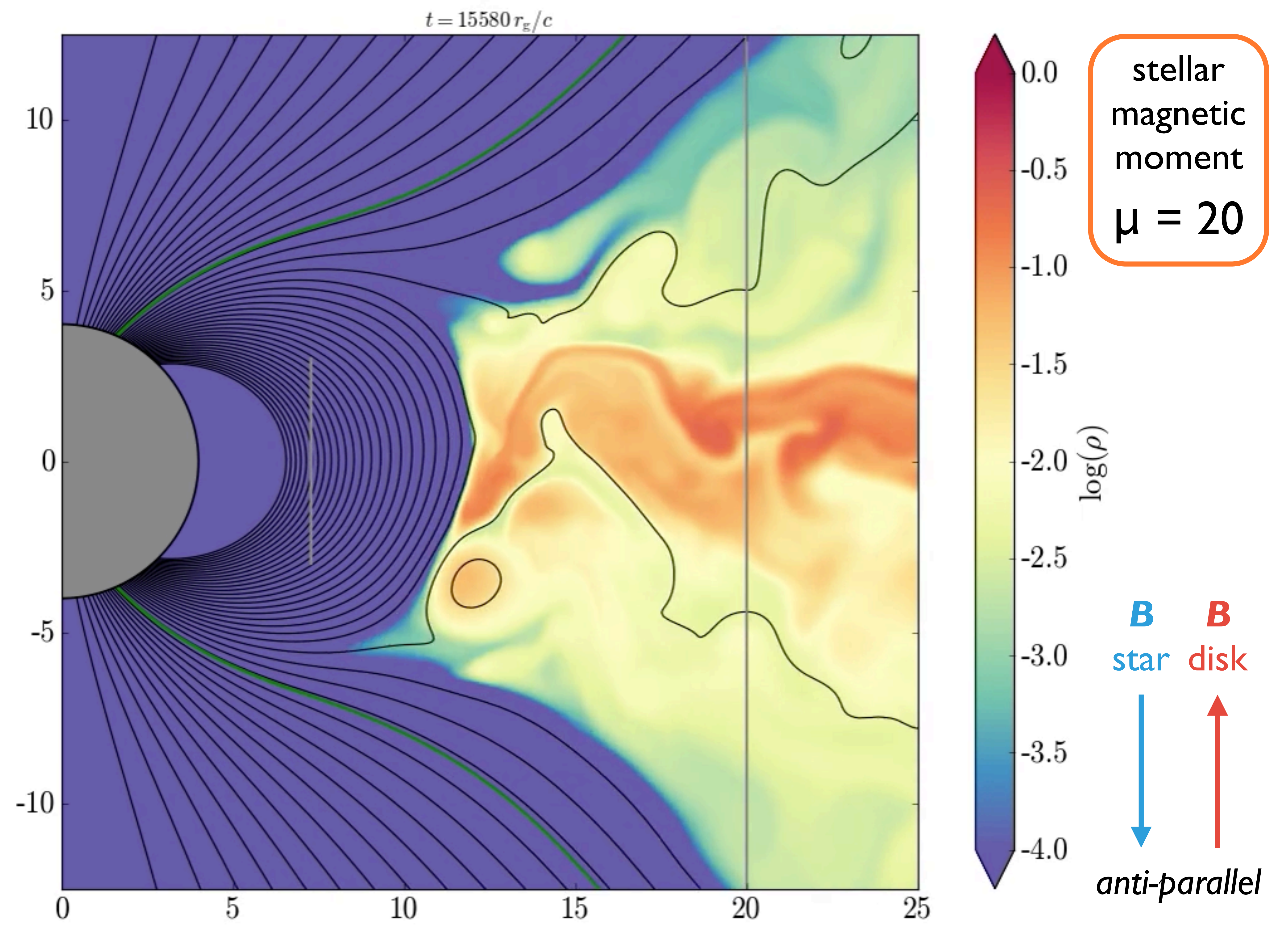
effective mass accretion rate

$$\dot{M} \sim \mu^{-2}$$

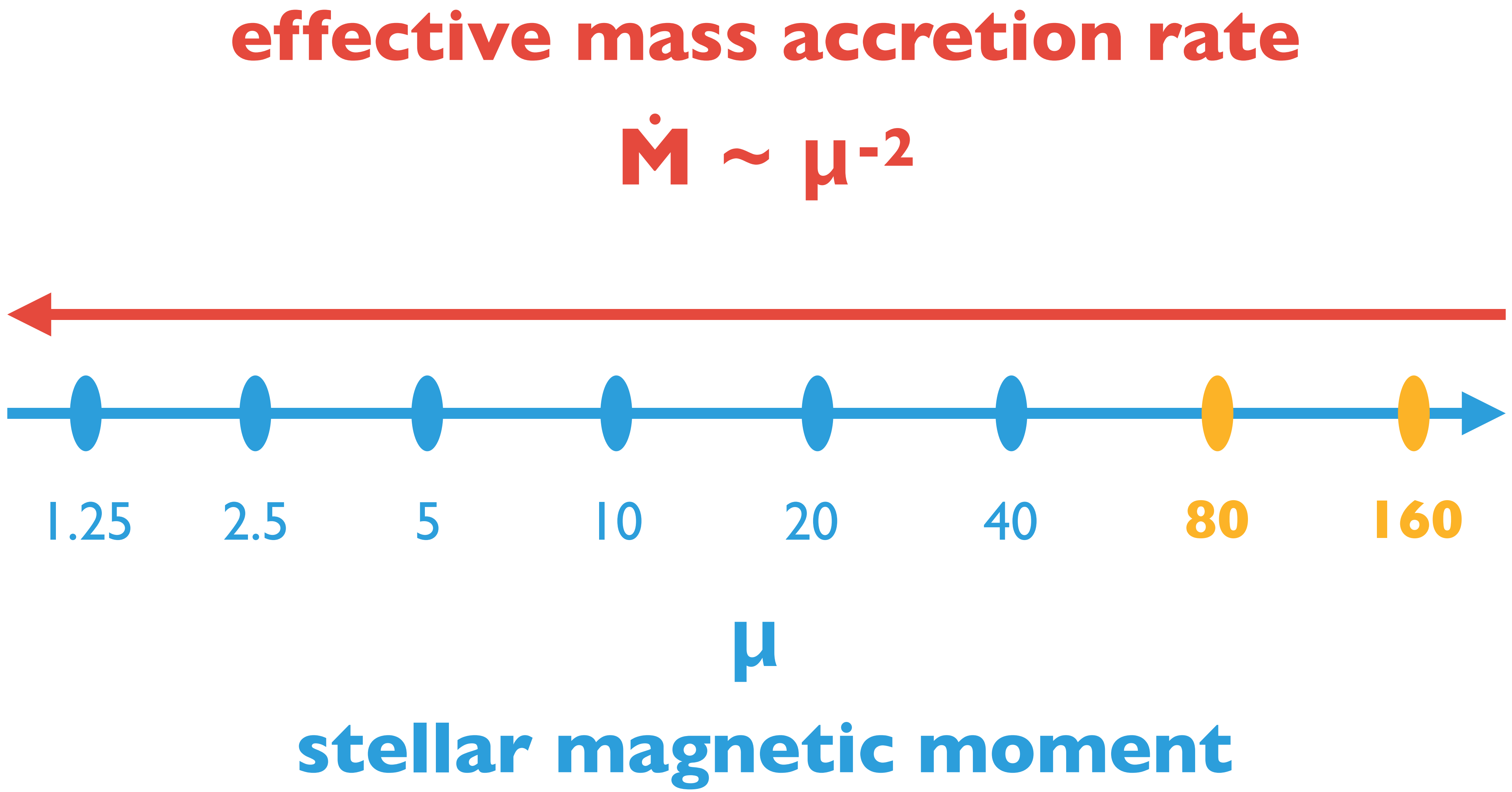


μ

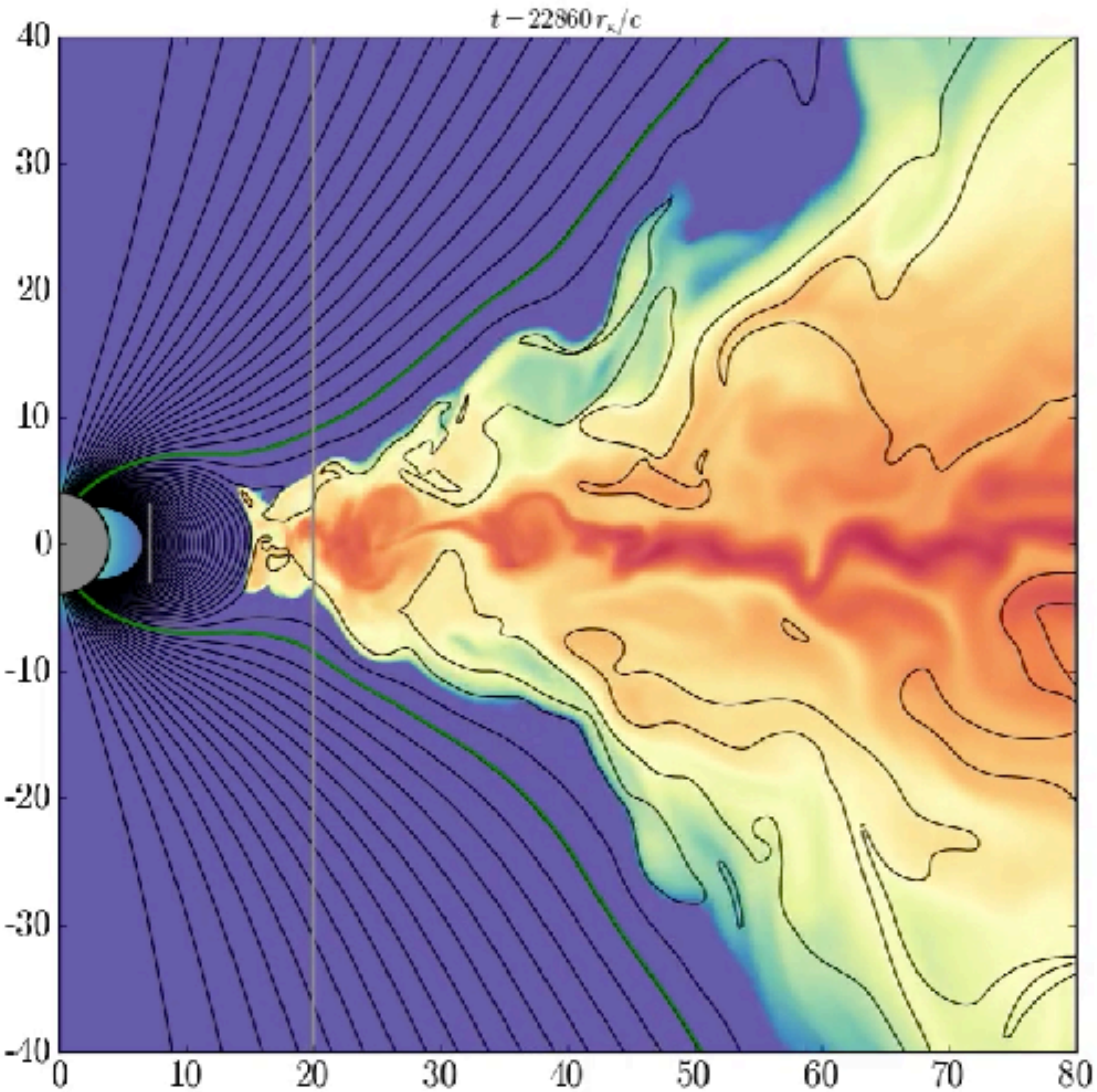
stellar magnetic moment



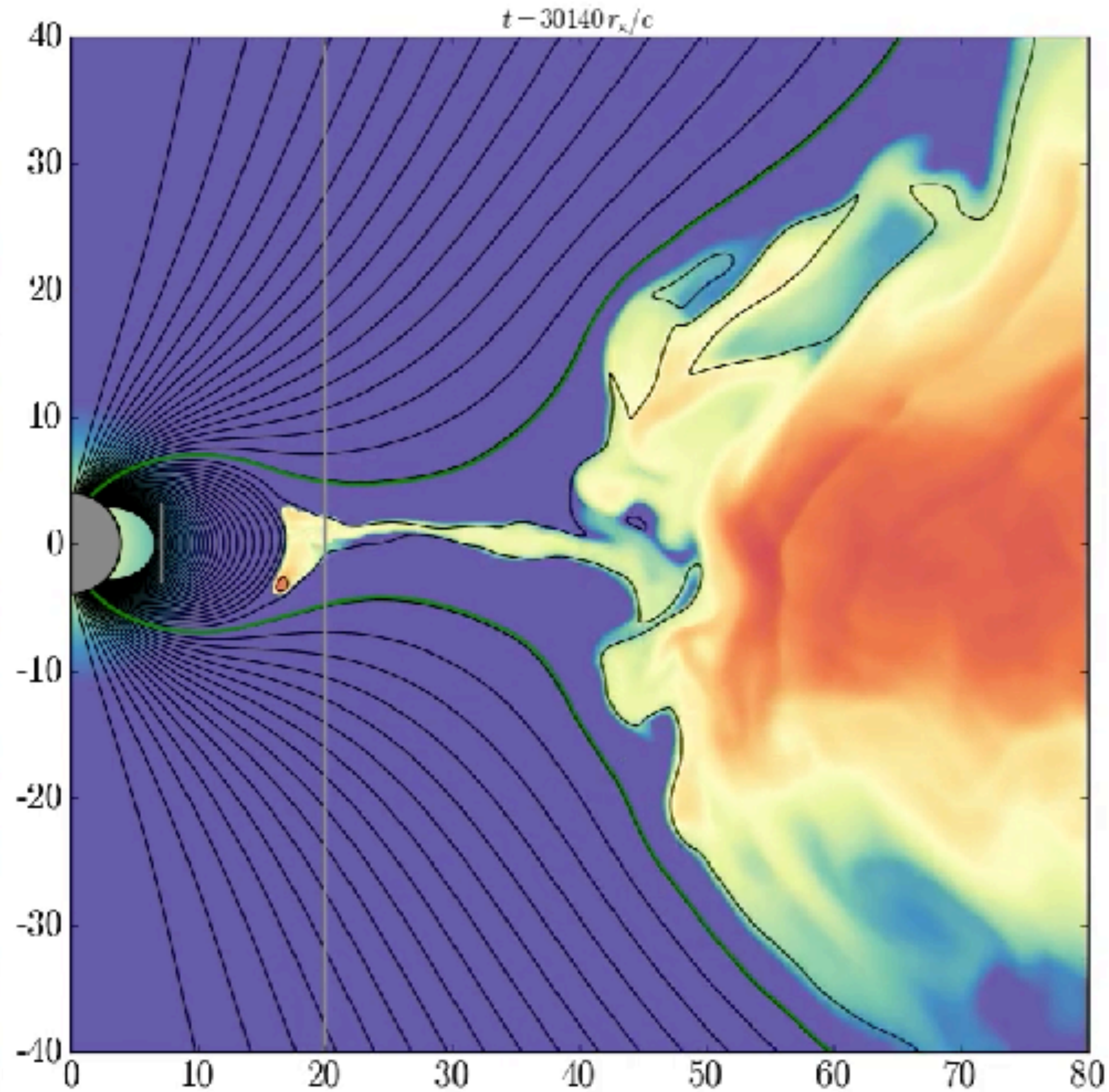
$t = 15580\, r_g/c$
log(ρ)
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
stellar magnetic moment
μ = 20
B star
B disk
anti-parallel

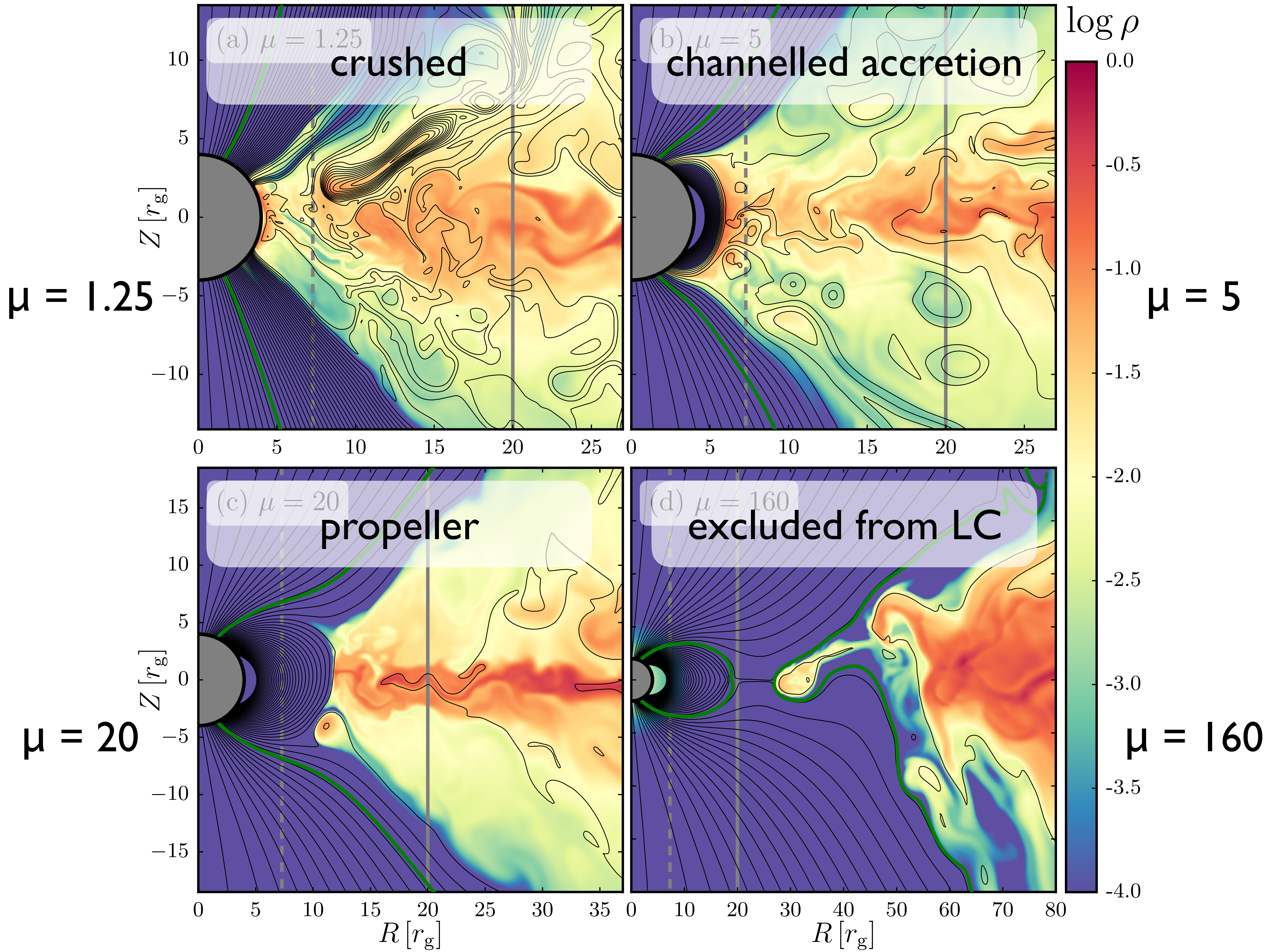

effective mass accretion rate
$\dot{M} \sim \mu^{-2}$
1.25
2.5
5
10
20
40
80
160
μ
stellar magnetic moment

μ = 80


t = 22860 r_s/c
40
30
20
10
0
-10
-20
-30
-40
0 10 20 30 40 50 60 70 80

μ = 160


t = 30140 r_s/c
40
30
20
10
0
-10
-20
-30
-40
0 10 20 30 40 50 60 70 80



(a) μ = 1.25
crushed
(b) μ = 5
channelled accretion
(c) μ = 20
propeller
(d) μ = 160
excluded from LC
μ = 1.25
μ = 5
μ = 20
μ = 160
log ρ
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
Z [r_g]
R [r_g]

Average values of:

magnetospheric radius

accretion rate

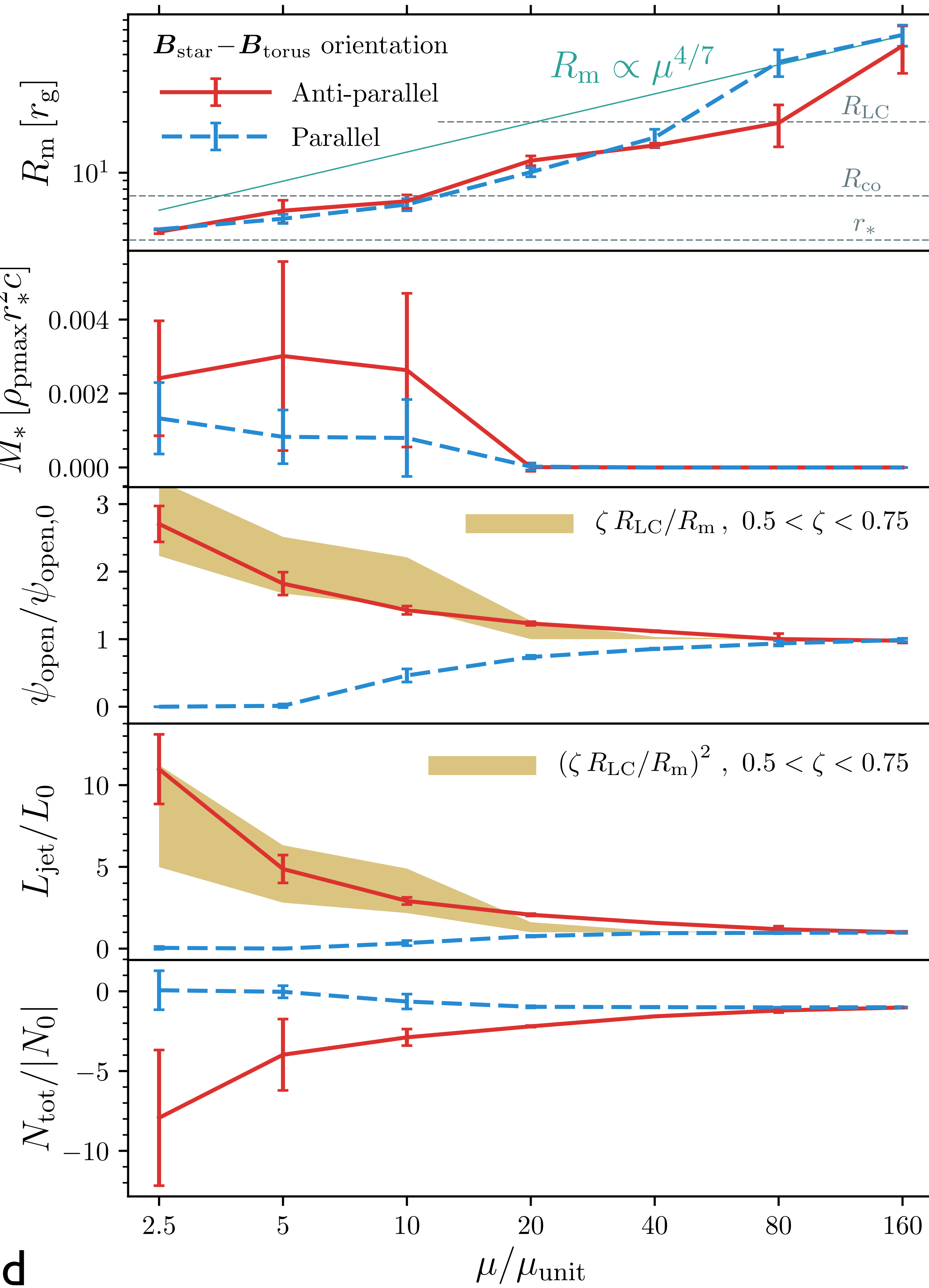
open flux

jet power

stellar torque

model

KP+ 2016



KP & Tchekhovskoy 2017

vertical bars: standard deviation over averaging period

Average values of:

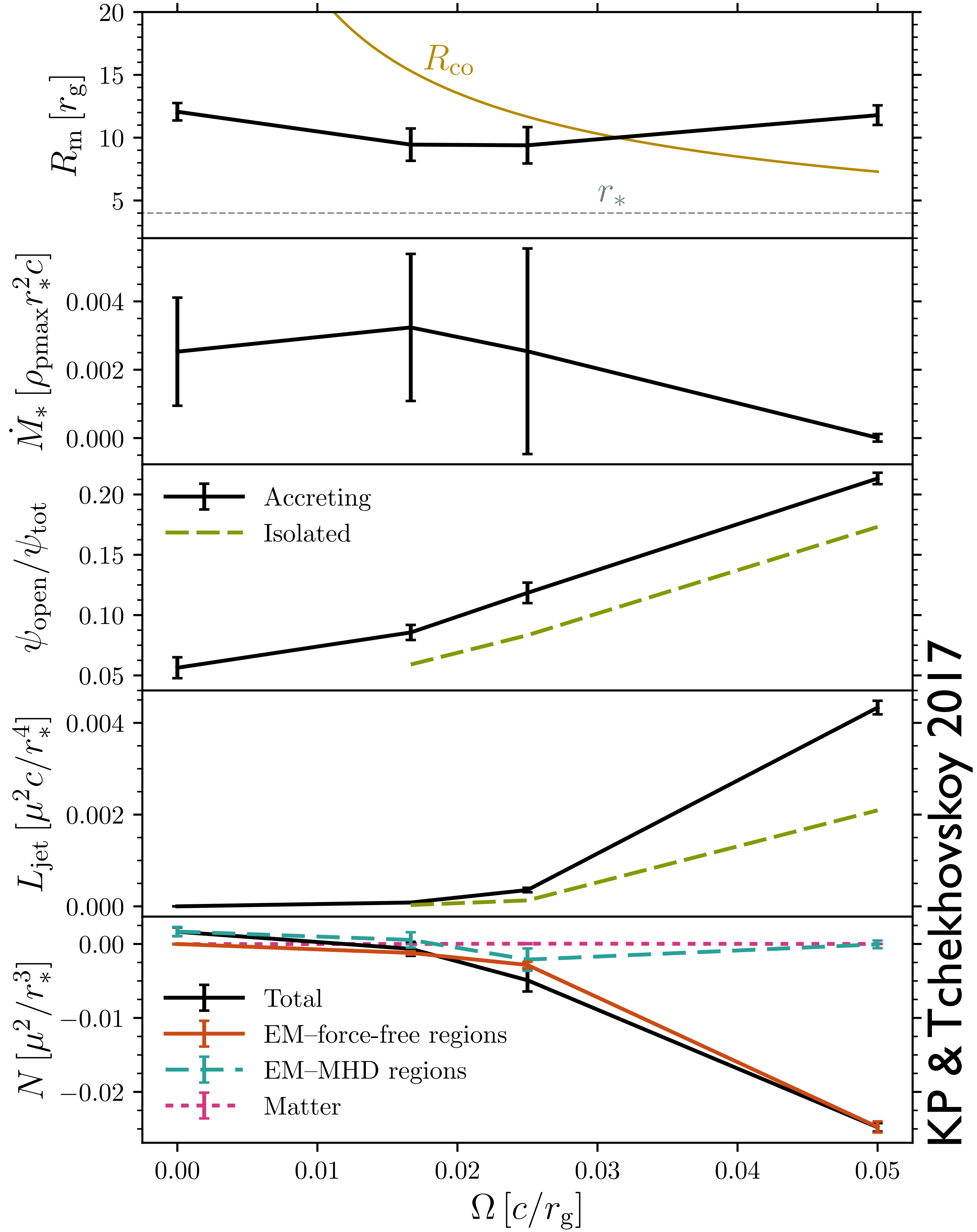
magnetospheric radius

accretion rate

open flux

jet power

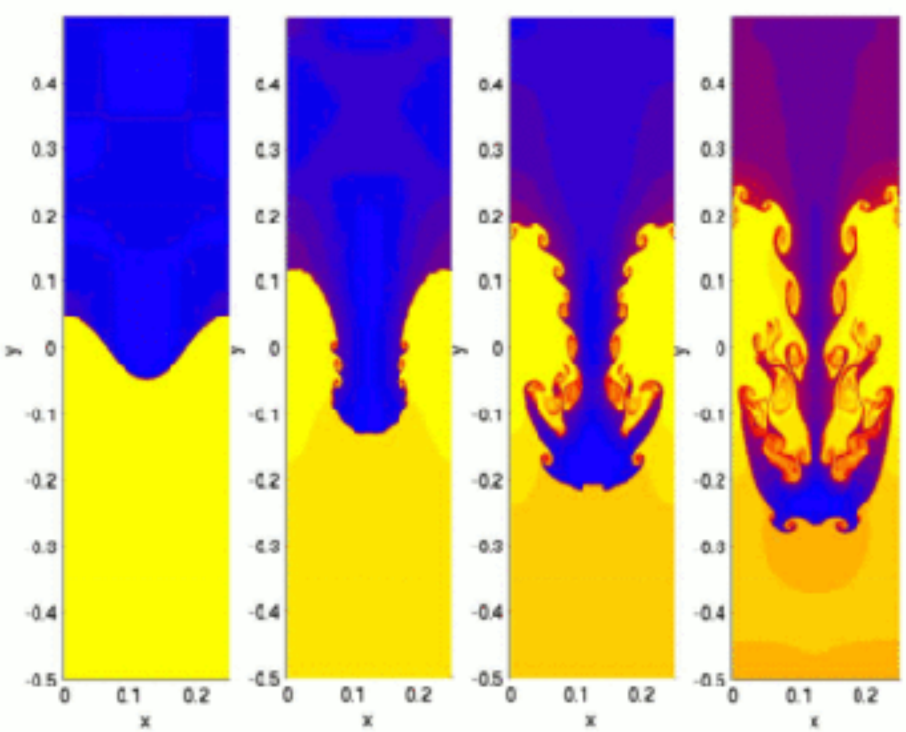
stellar torque



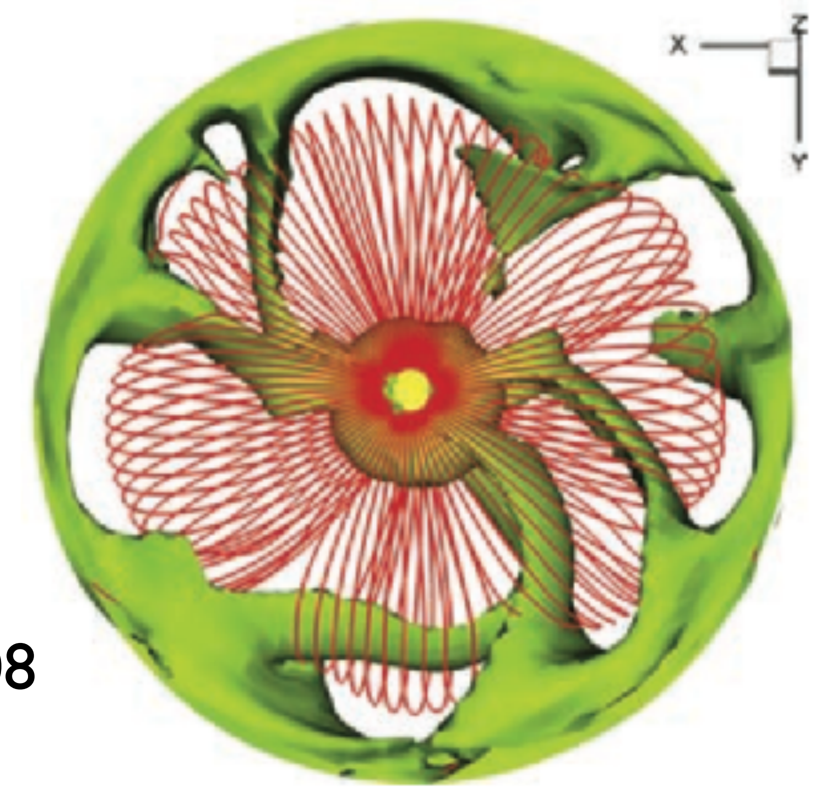
vertical bars: standard deviation over averaging peric

3D simulations

1. Need 3D for realistic MRI turbulent dynamo
2. Interchange instability: accretion through closed-field region



Magnetic Rayleigh-Taylor / Interchange

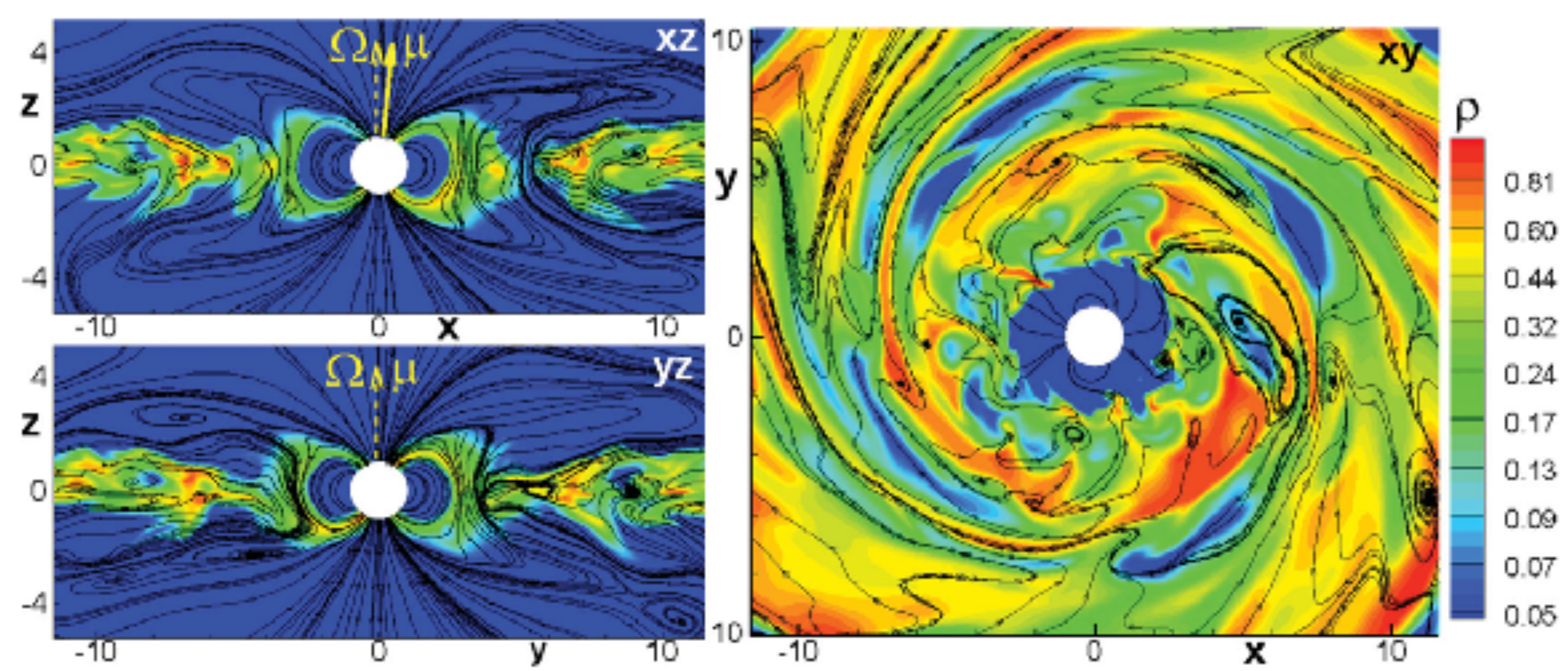


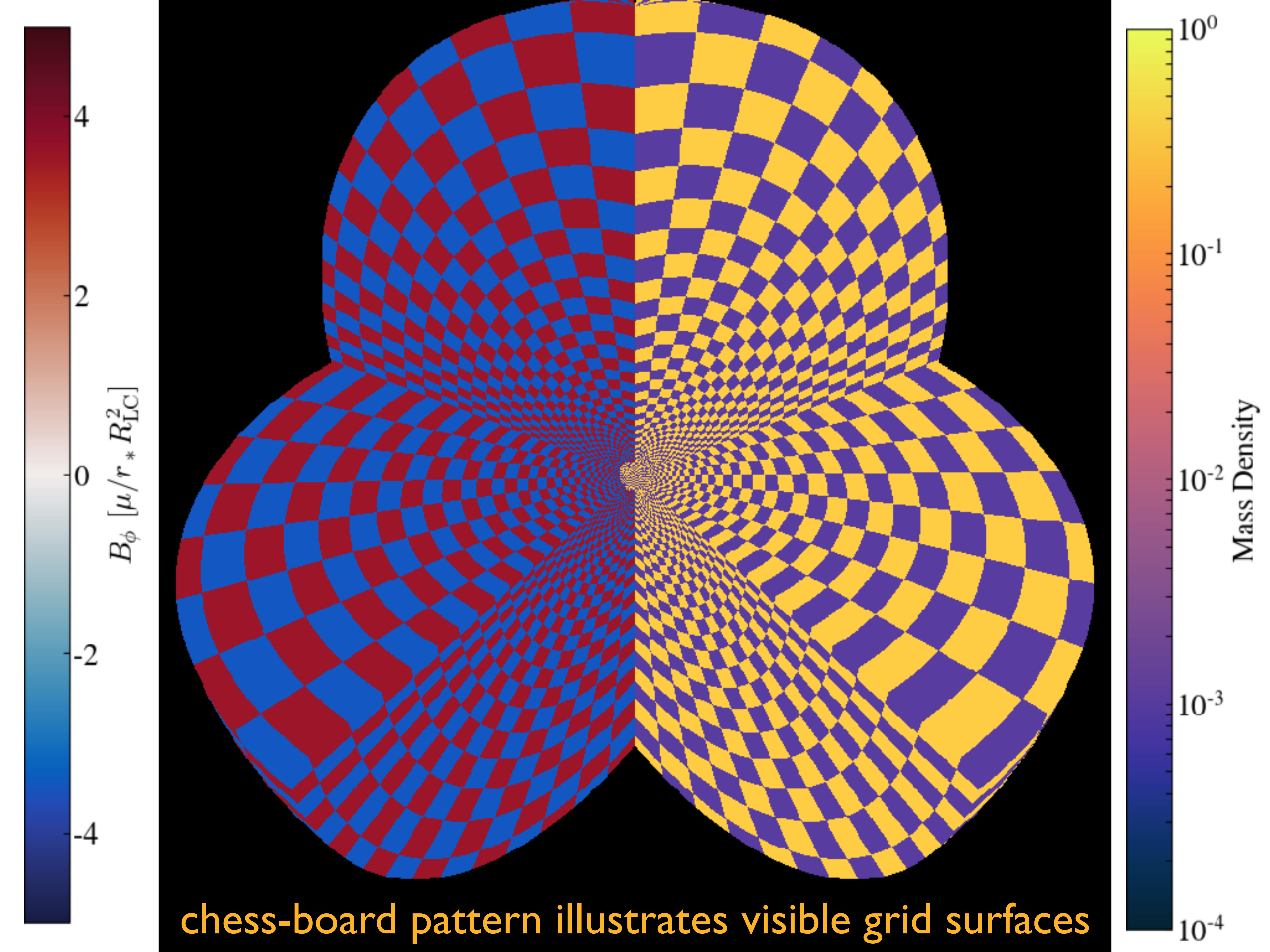
alpha-prescription resistive MHD

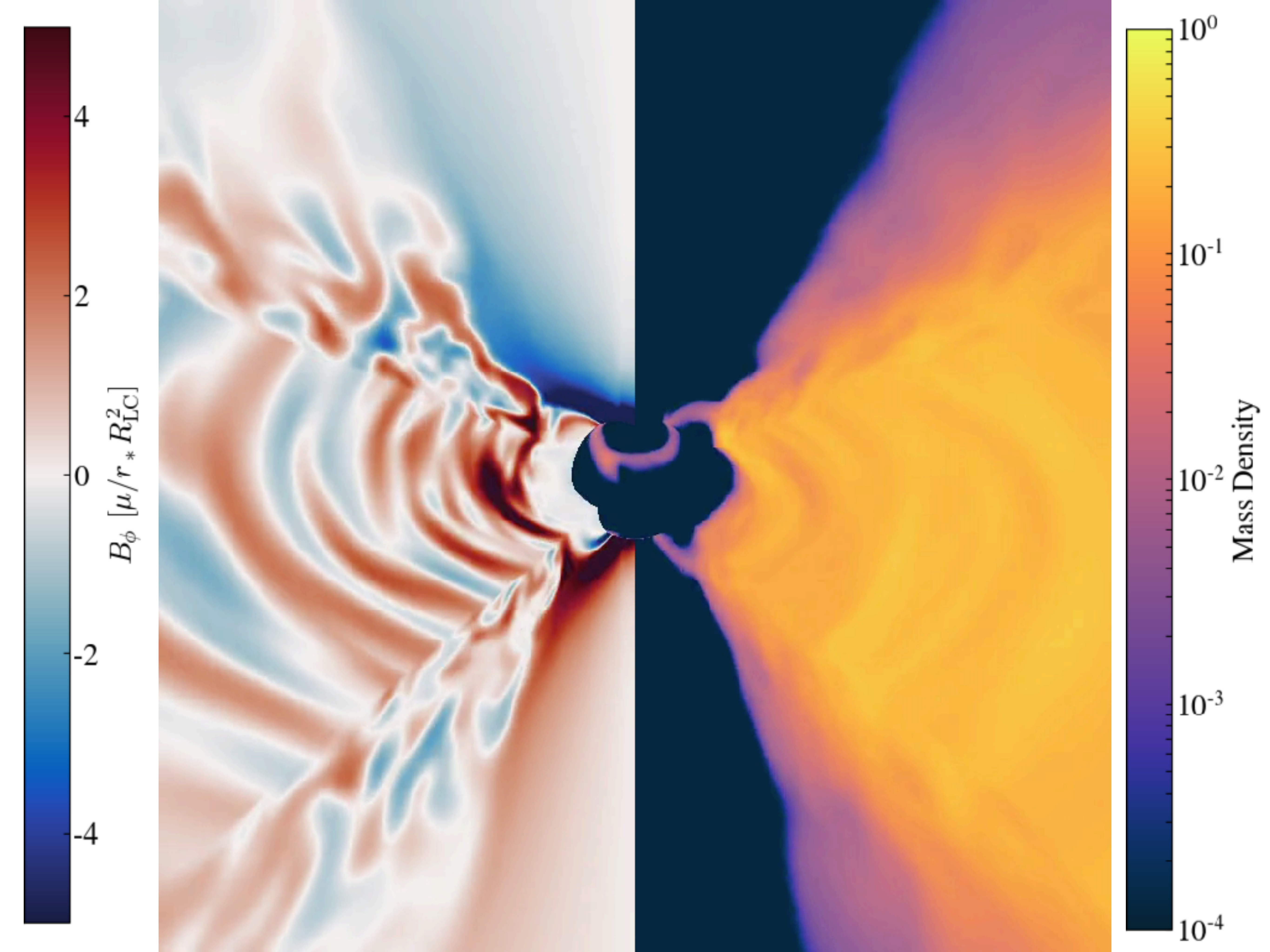
Kulkarni & Romanova 2008

Ideal MHD/MRI disc

Romanova+ 2012



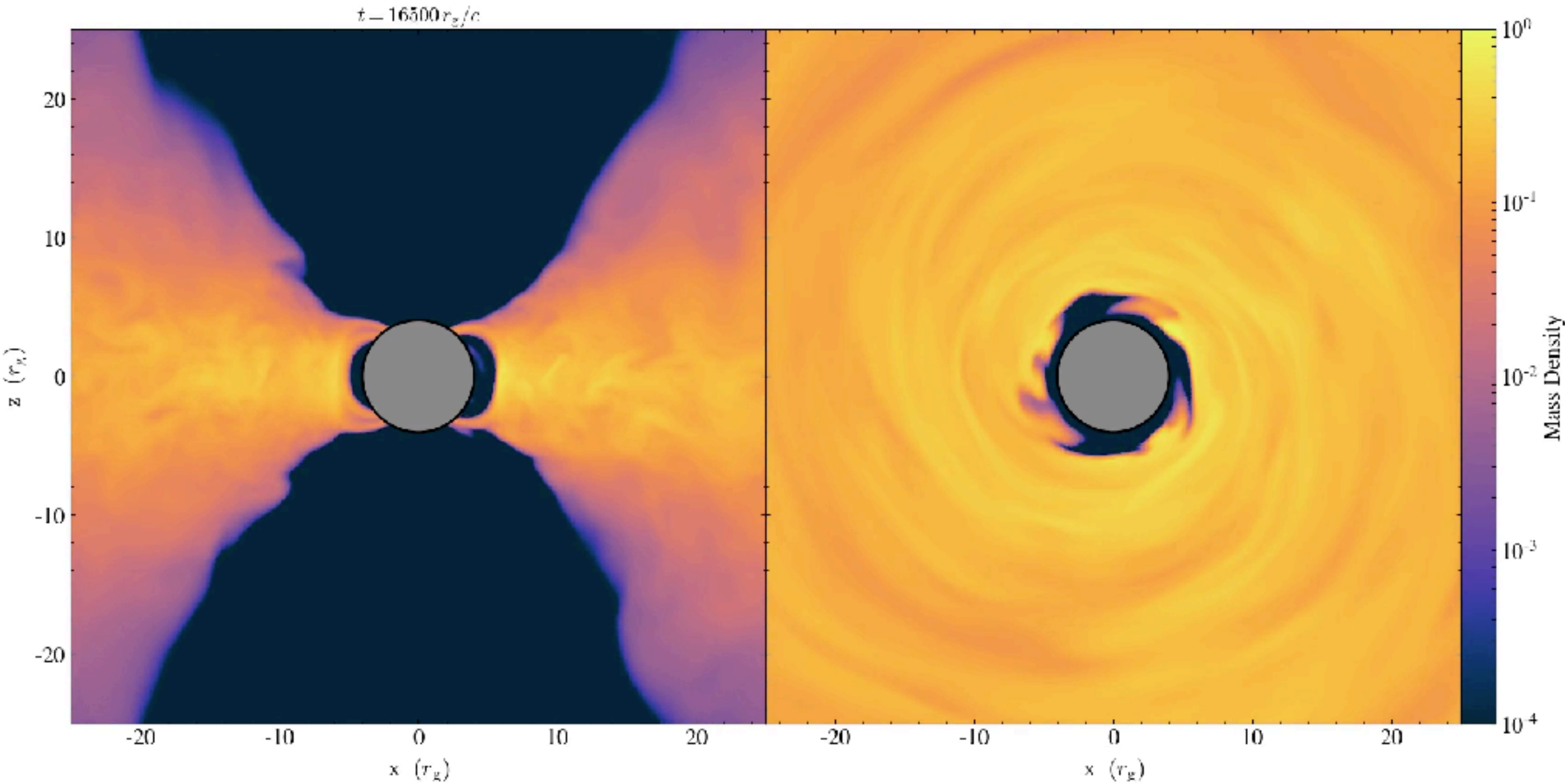

$B_\phi \ [\mu / r_* R_{LC}^2]$
4
2
0
-2
-4
Mass Density
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
chess-board pattern illustrates visible grid surfaces

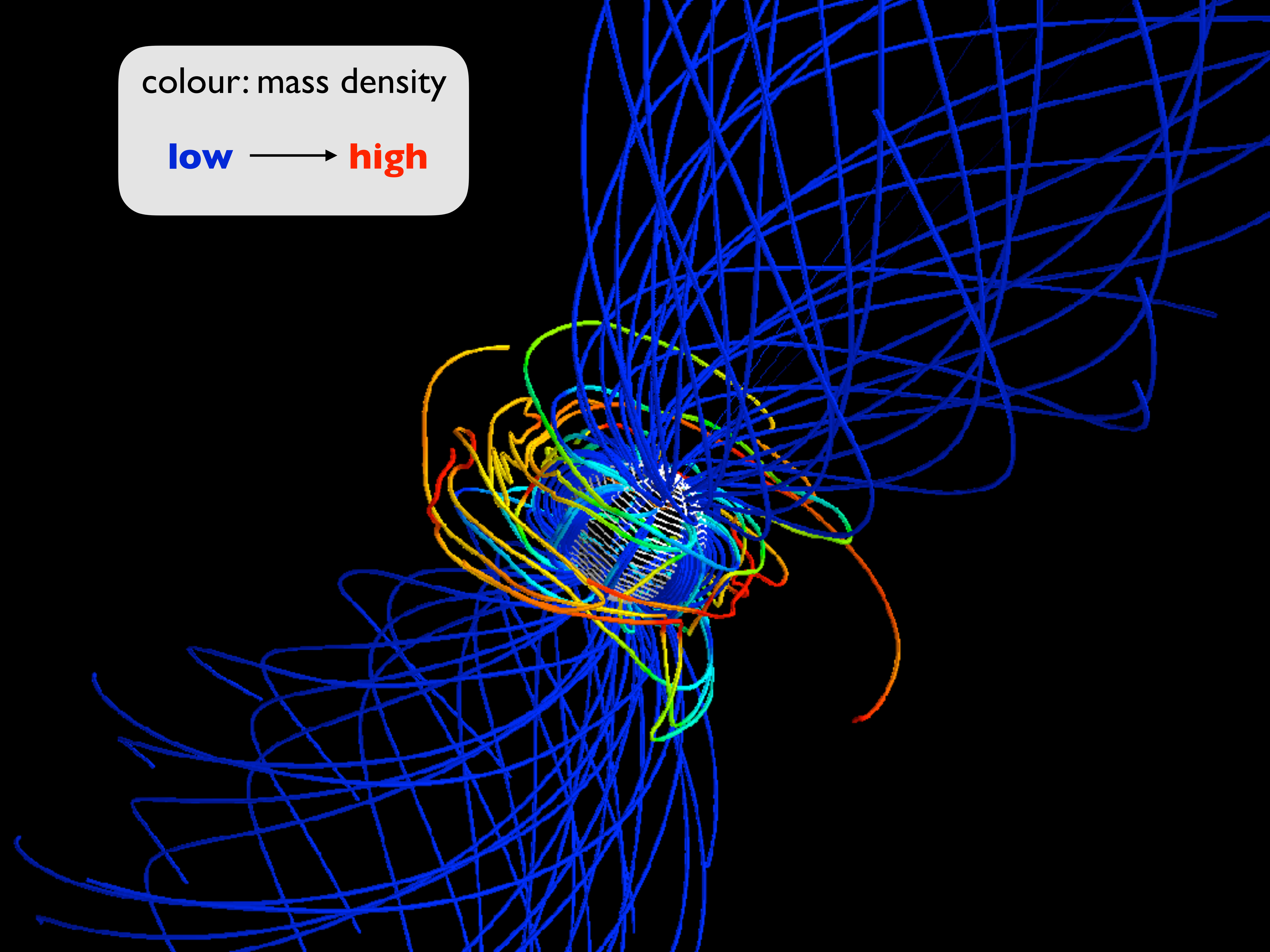


4
2
0
-2
-4
$B_\phi\ [\mu/r_*R_{\rm LC}^2]$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Mass Density

stellar magnetic moment: μ = 10

light cylinder: R_{LC} = 20

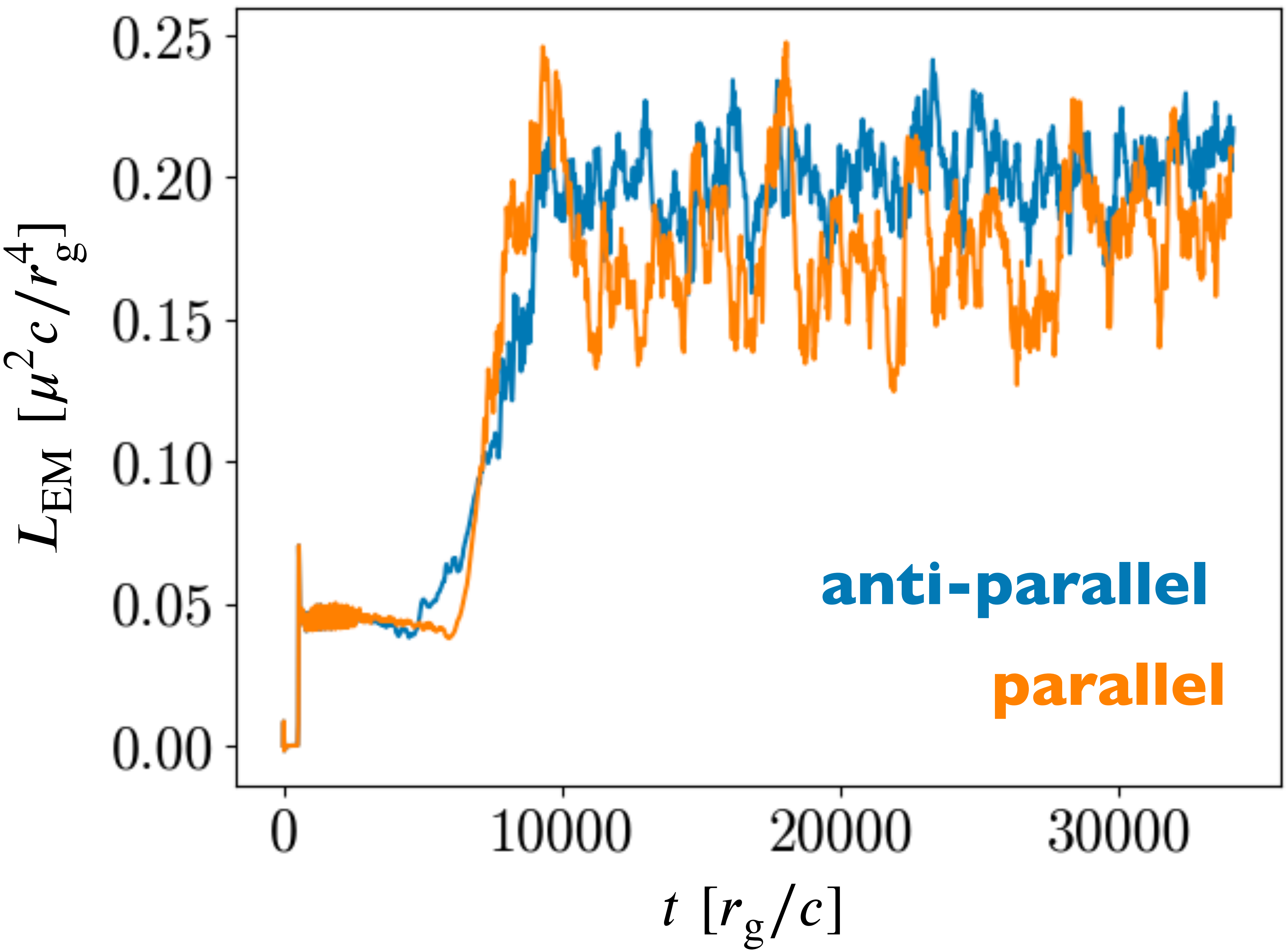



colour: mass density
low → high

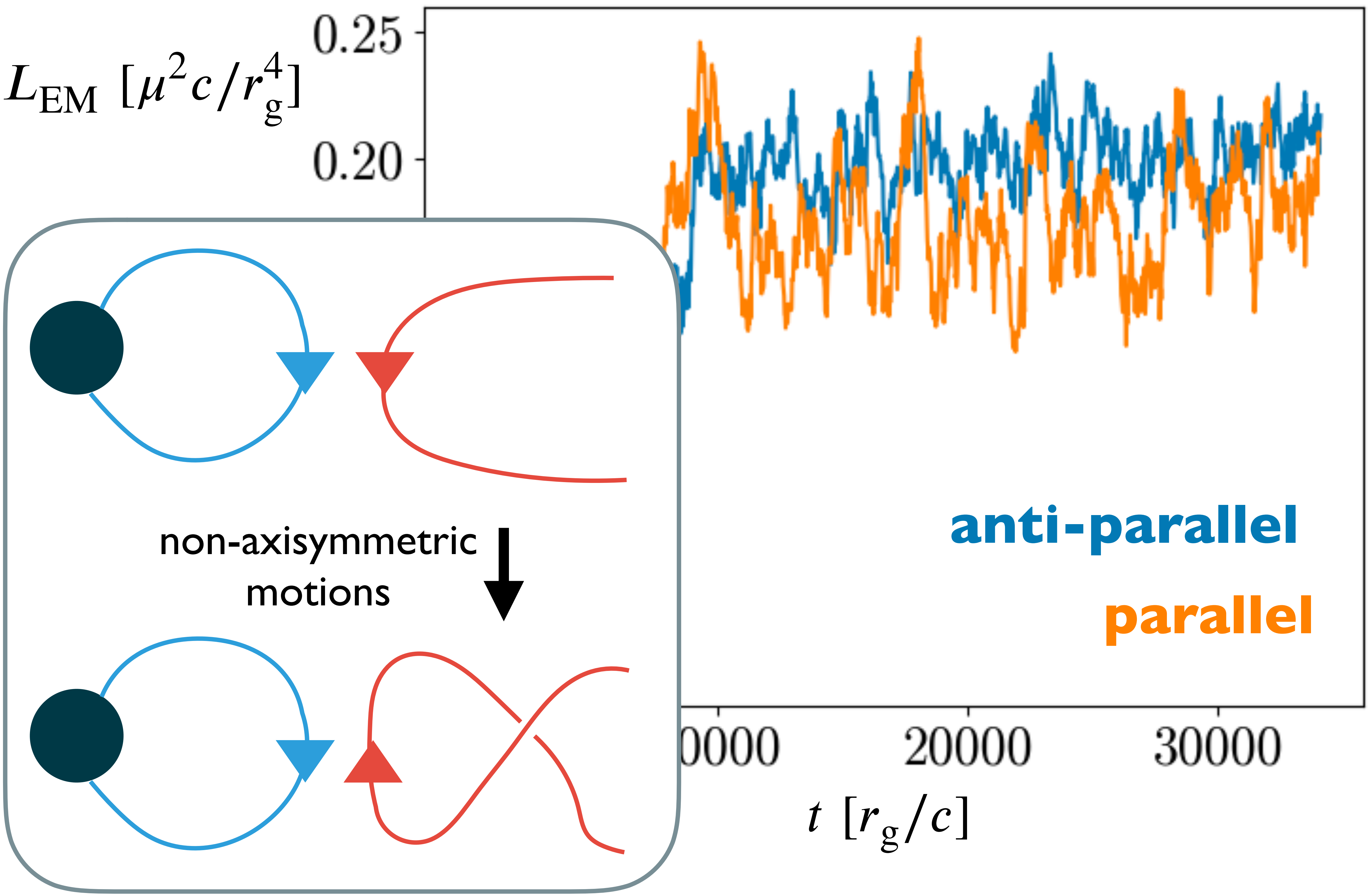
Star–torus initial relative ***B*** orientation

KP & Tchekhovskoy, in prep

EM jet power in nearly force-free region

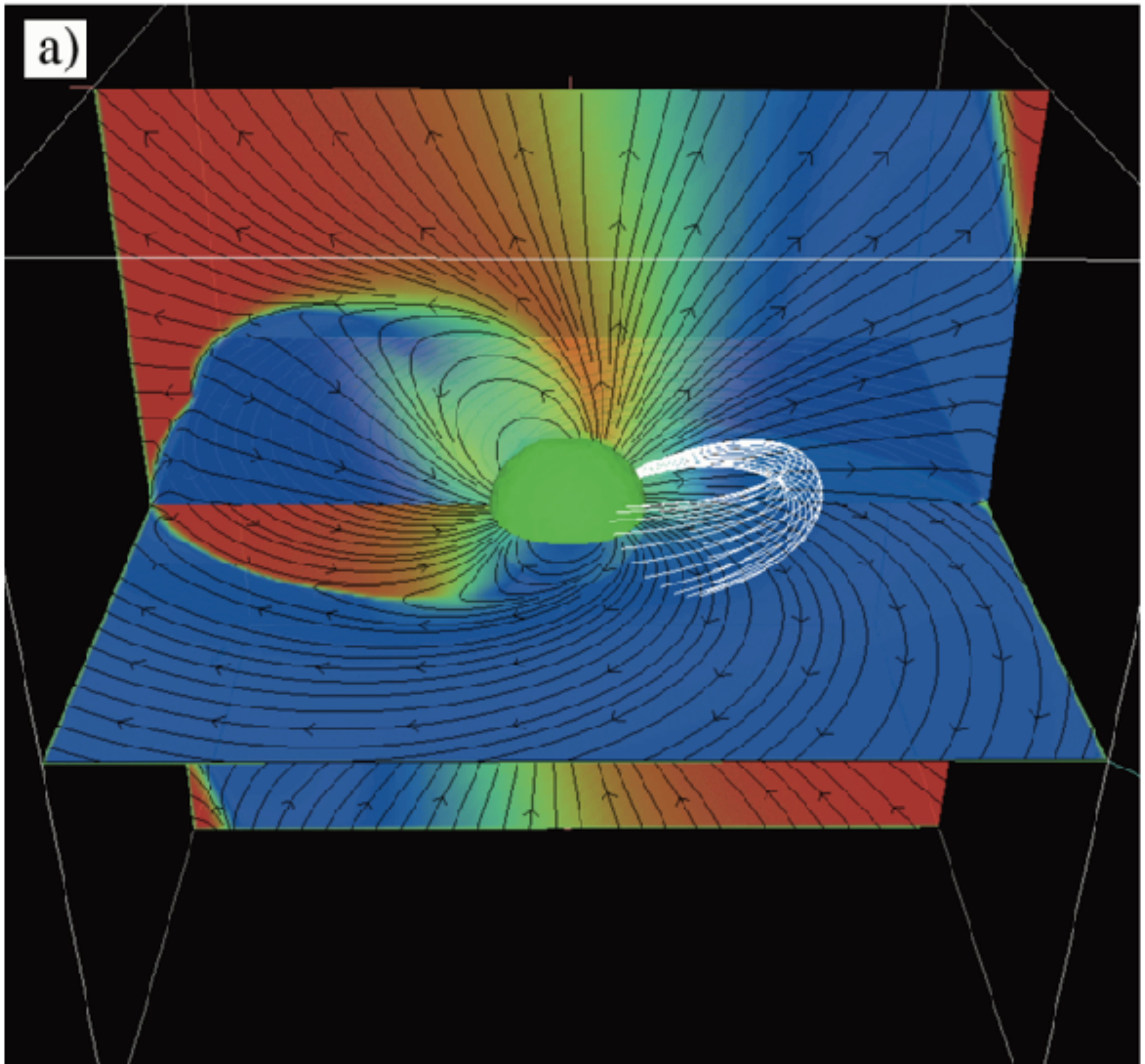


Star–torus initial relative $\boldsymbol{B}$ orientation



Oblique rotators

Misaligned rotation and magnetic axes: true pulsars



isolated pulsar

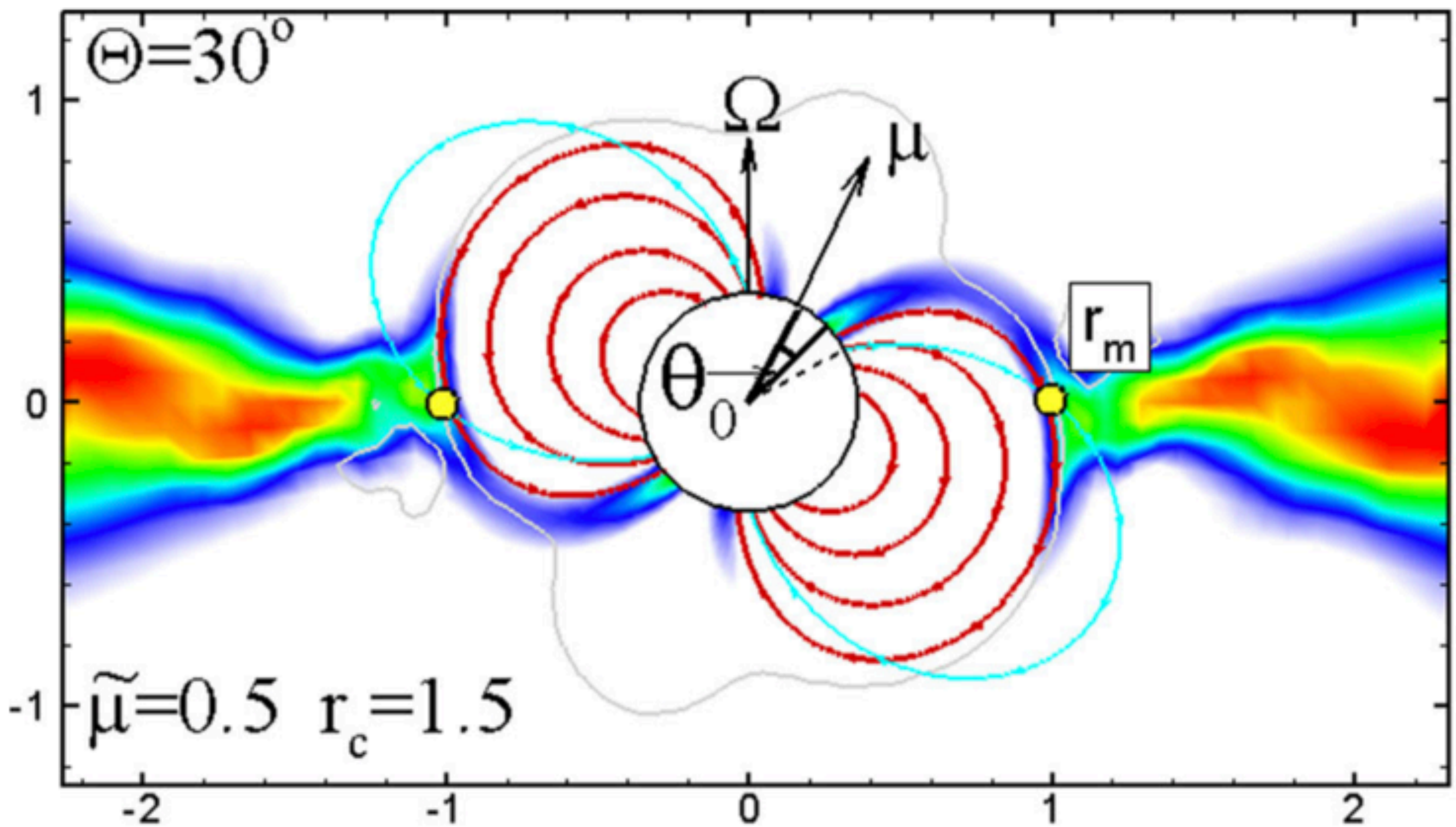
colour: toroidal ***B***

χ = 60°

Spitkovsky 2006

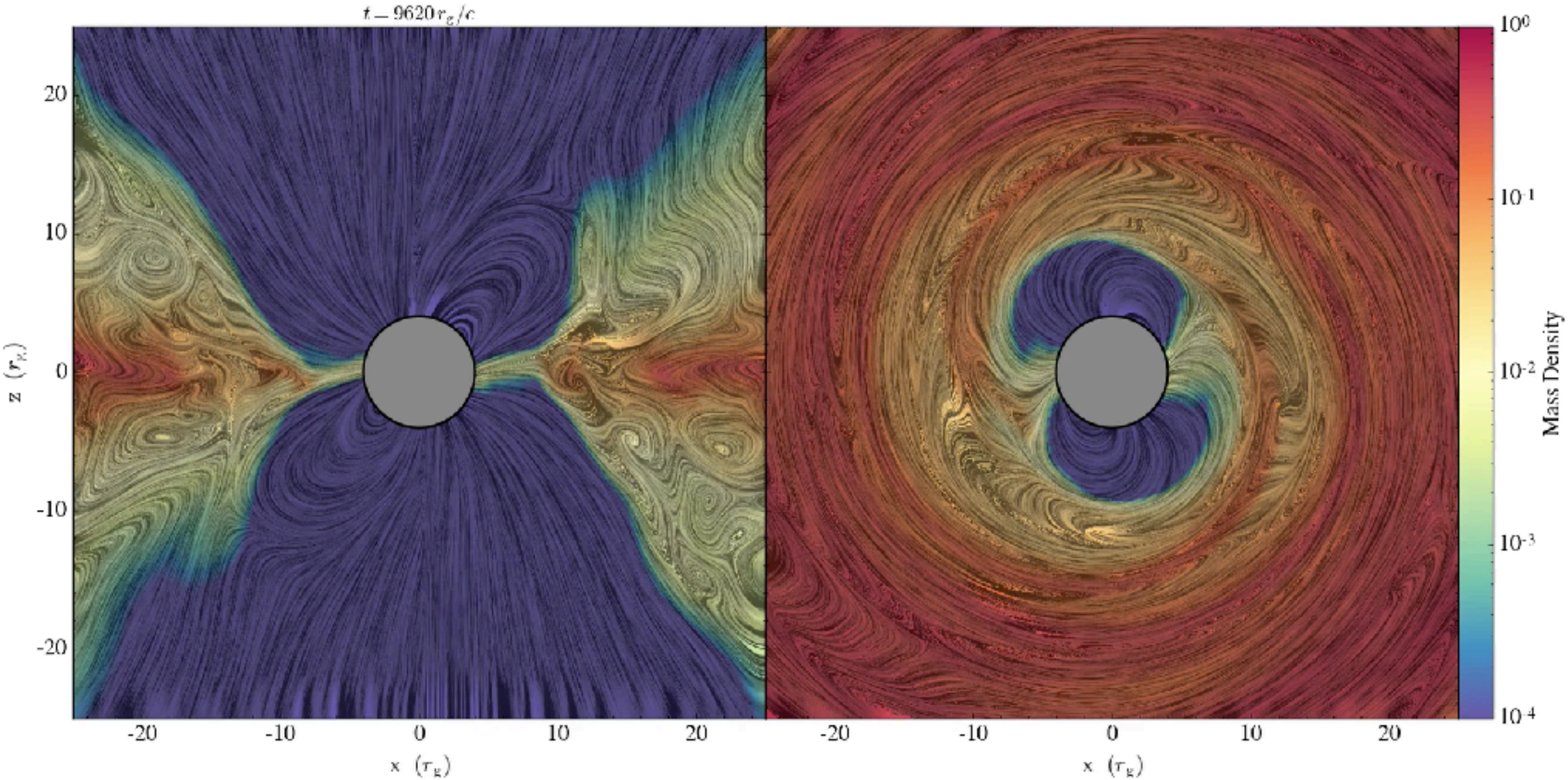
Accretion curtains → streams

Kulkarni & Romanova 2013



Disc: entropy-conserving ∴ thin; α-viscosity stellar magnetic moment: $\mu = 10$

$\chi = 45°$



Jet Launching Agent

central rotating object **vs** inner accretion flow

inner accretion flow → Blandford-Payne

central rotating object →

- protostar
- neutron star → electromagnetic "enhanced pulsar wind"
- black hole → Blandford-Znajek

Jet Launching Agent

central rotating object **vs** inner accretion flow

hard to avoid baryon loading

protostar

neutron star

black hole

can give a clean, high-Γ jet

Summary

First (general-) relativistic simulations of pulsar accretion

Four regimes: crushed / accreting / propeller / excluded from light cylinder

Efficient flux opening — weak star-disc magnetic coupling

— relativistic jets

Force-free & MHD simulations support simple model for torques & jets

3D is important (realistic turbulence & interchange instability)

7 movies of axisymmetric runs on YouTube: link at **1708.06362** arXiv listing