Relativistic Accretion onto Millisecond Pulsars

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National Laboratory

with
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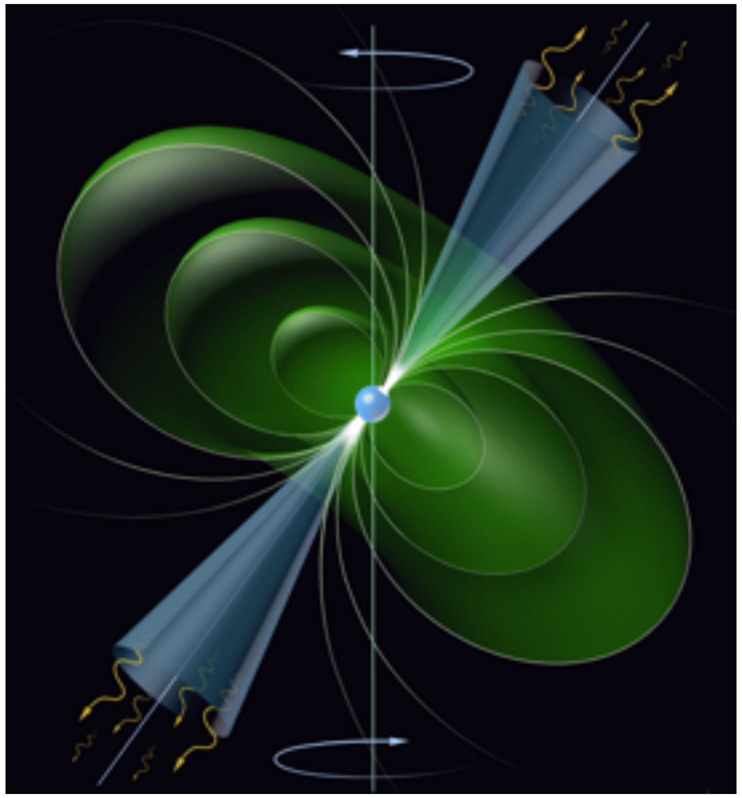
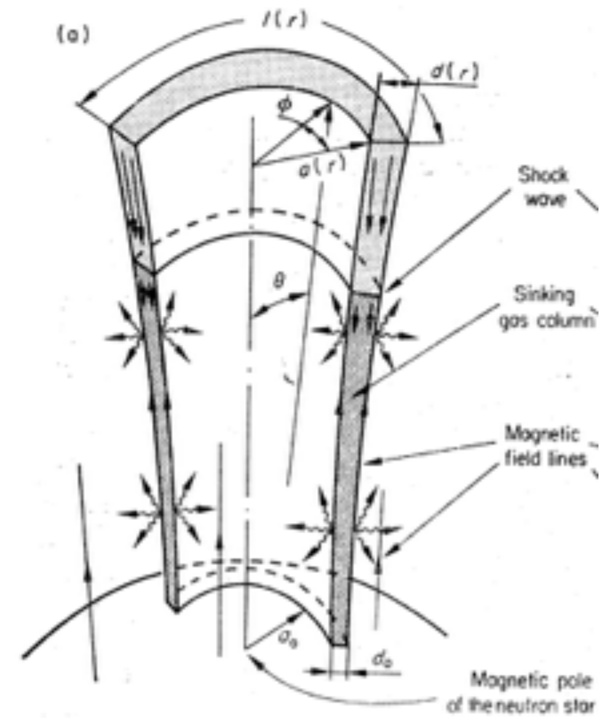
Einstein Fellows Symposium, October 12, 2017

Millisecond Pulsar Families

radio



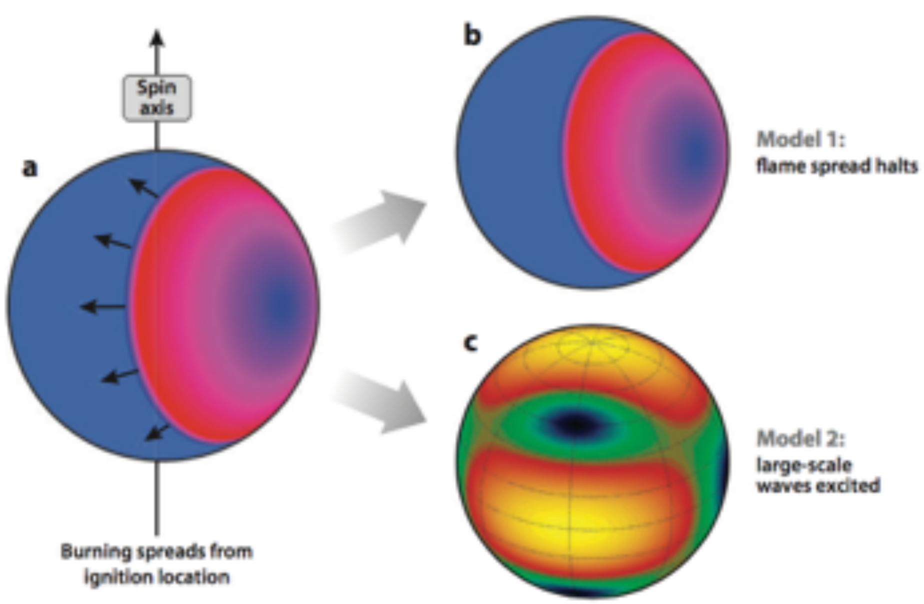
accretion-powered



X-rays from accretion column

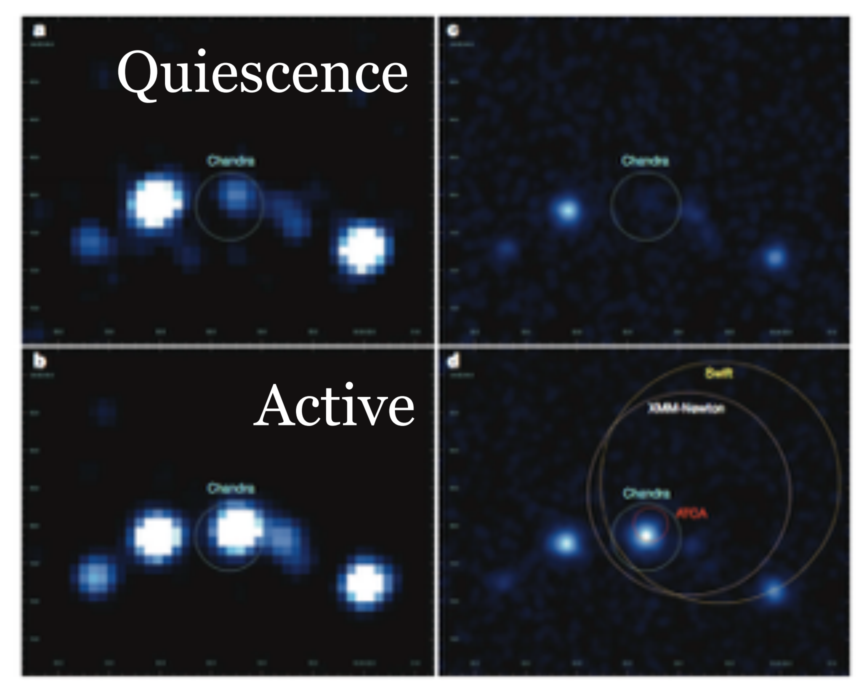
Basko & Sunyaev '76

nuclear-powered



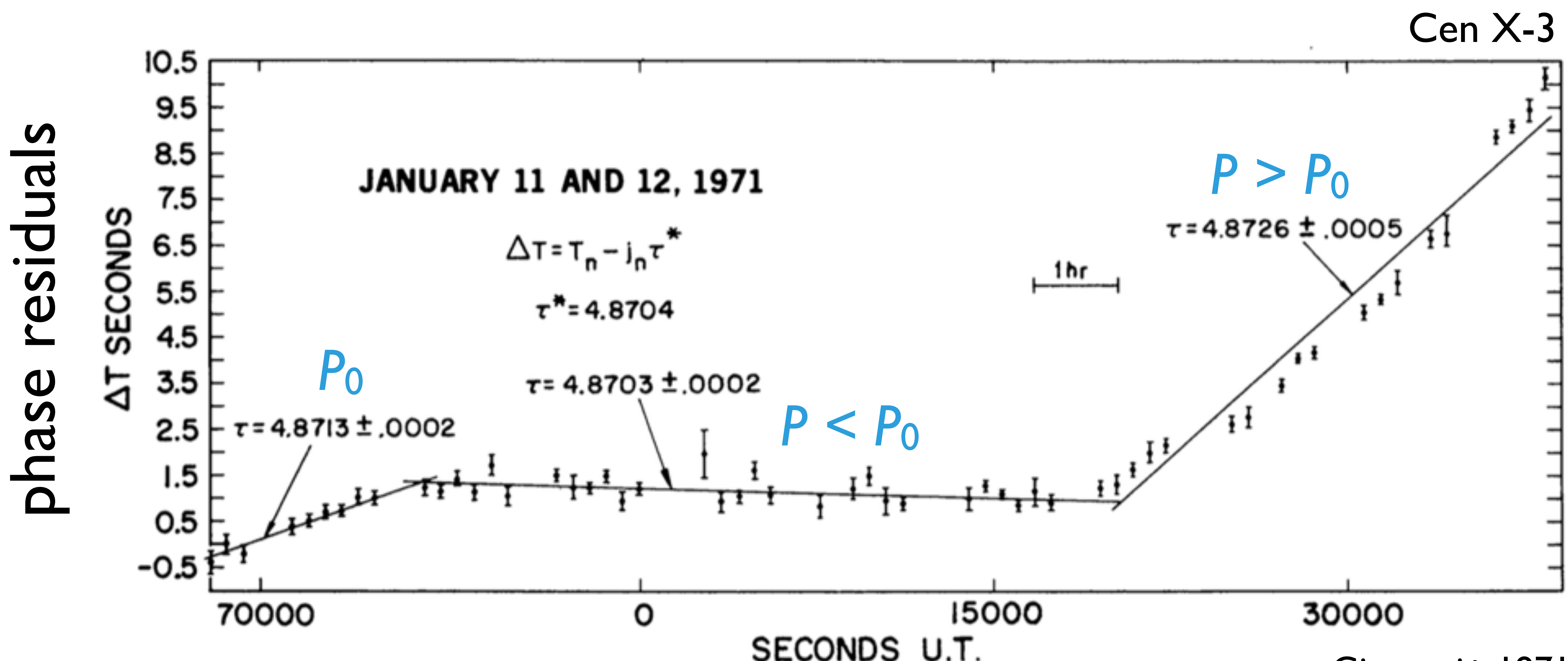
Watts 2012

transitional



Papitto+ 2013

Changing pulsar spin periods

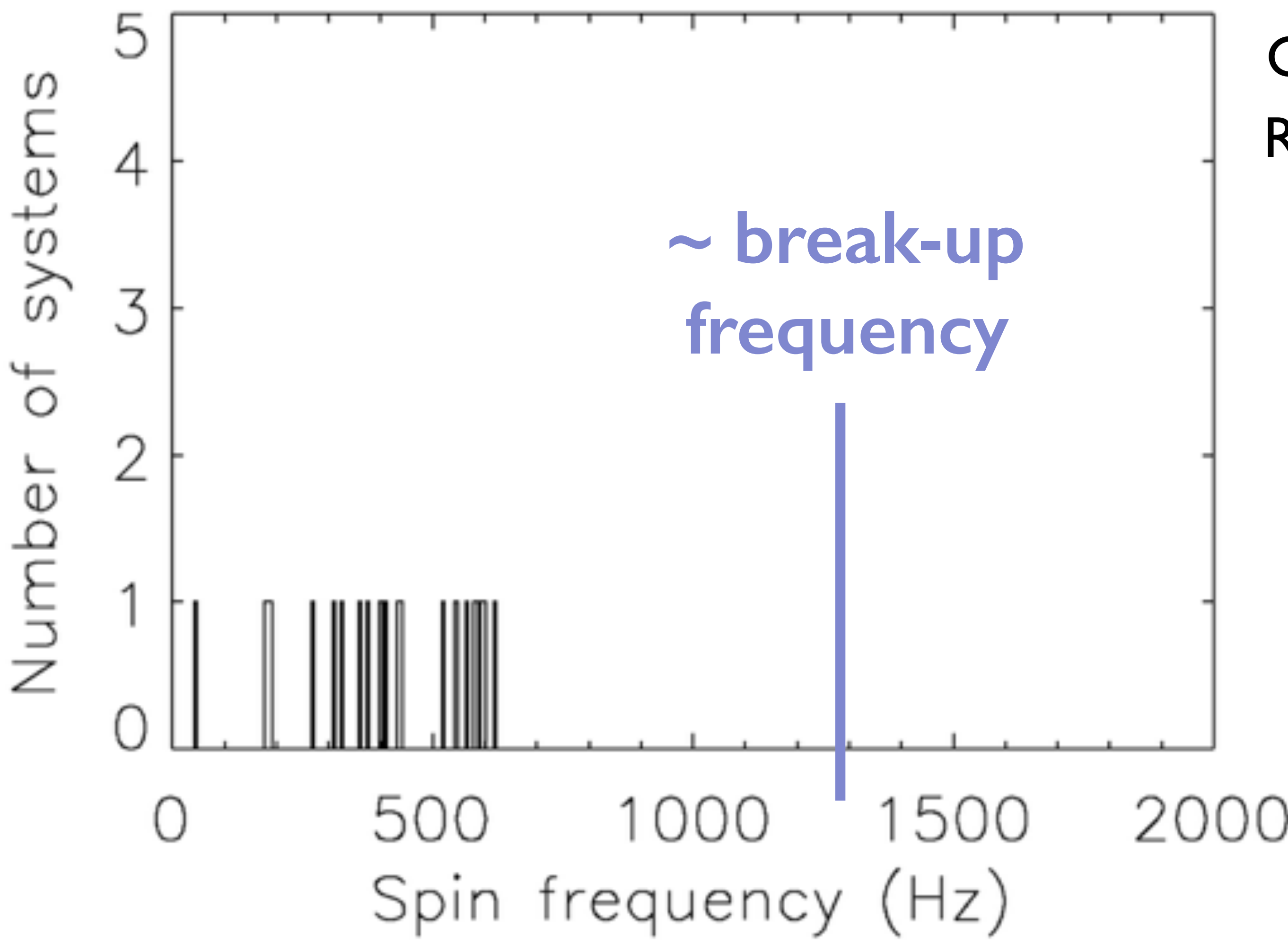


Giacconi+ 1971

UHURU satellite

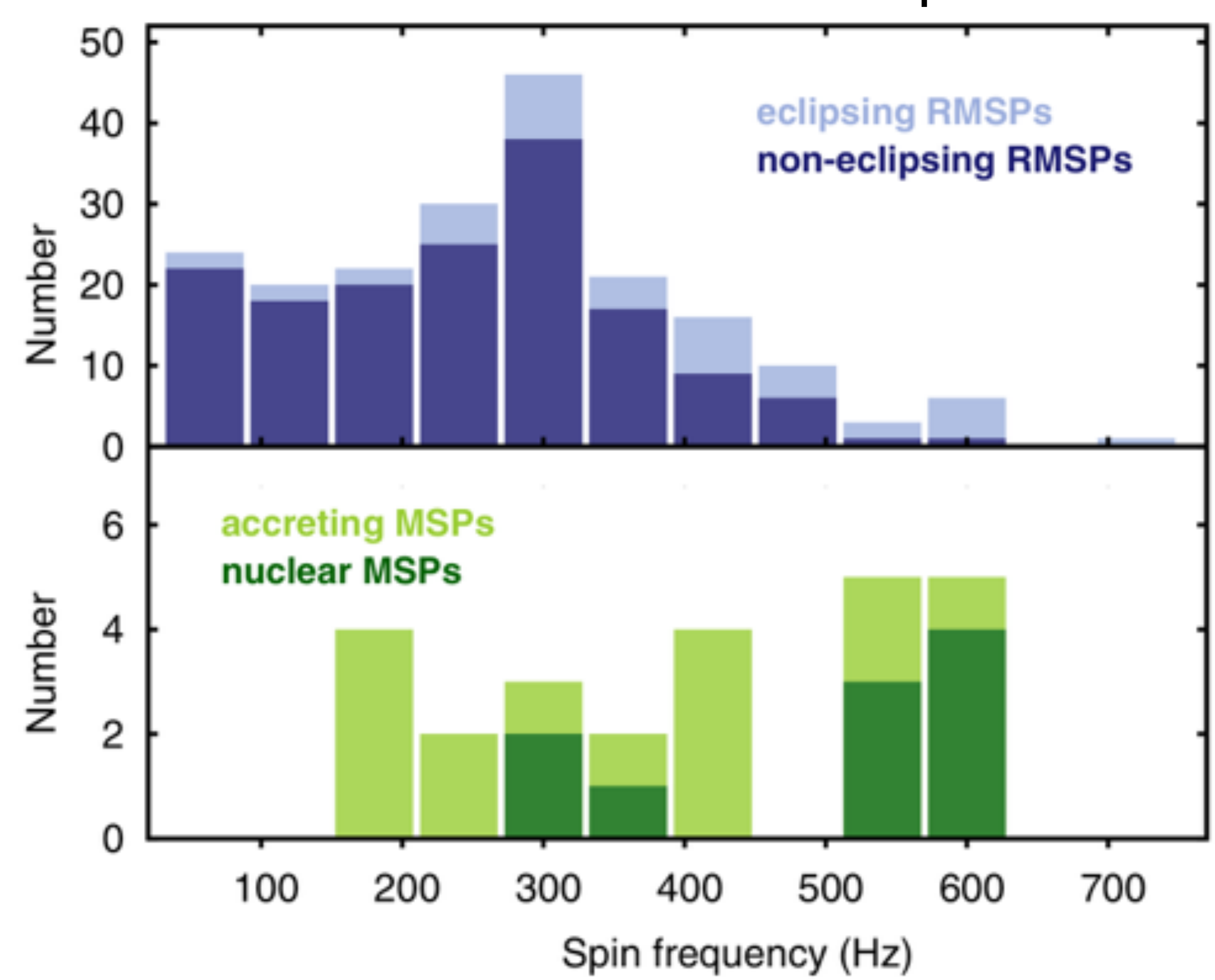
P: spin period

Millisecond pulsar spin-frequency distribution

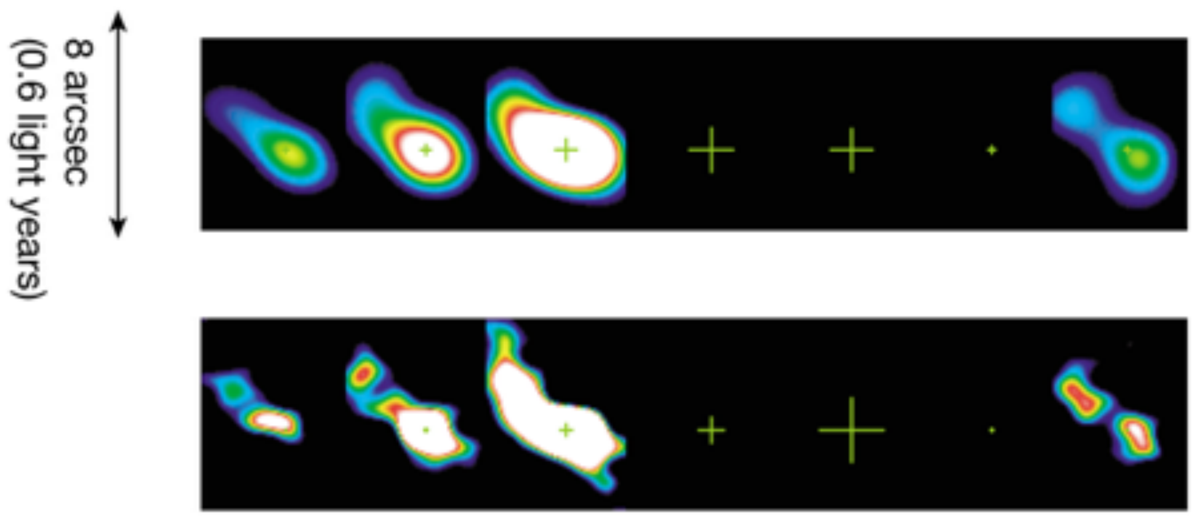


Chakrabarty 2008
RXTE

Papitto+ 2014



Jets from neutron stars



Fender+ 2004

Cir X-1 : $\Gamma > 15$?

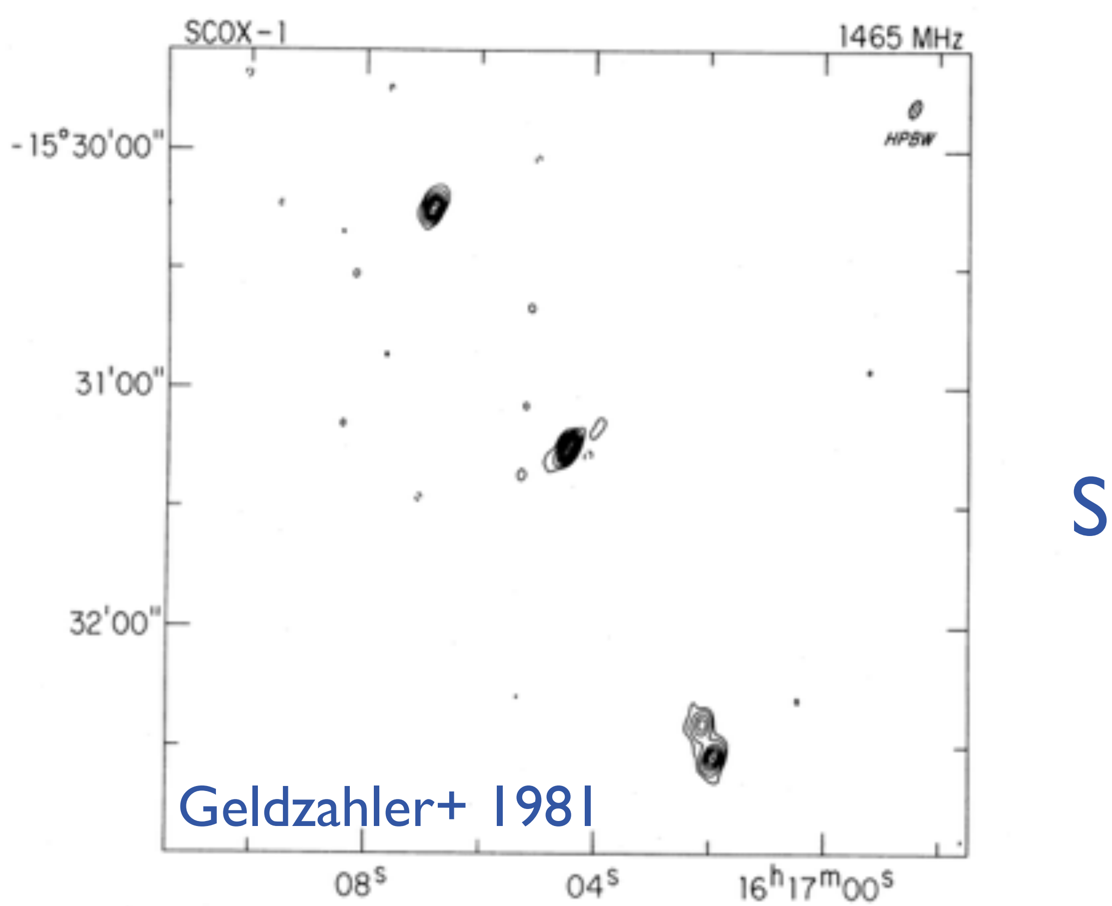
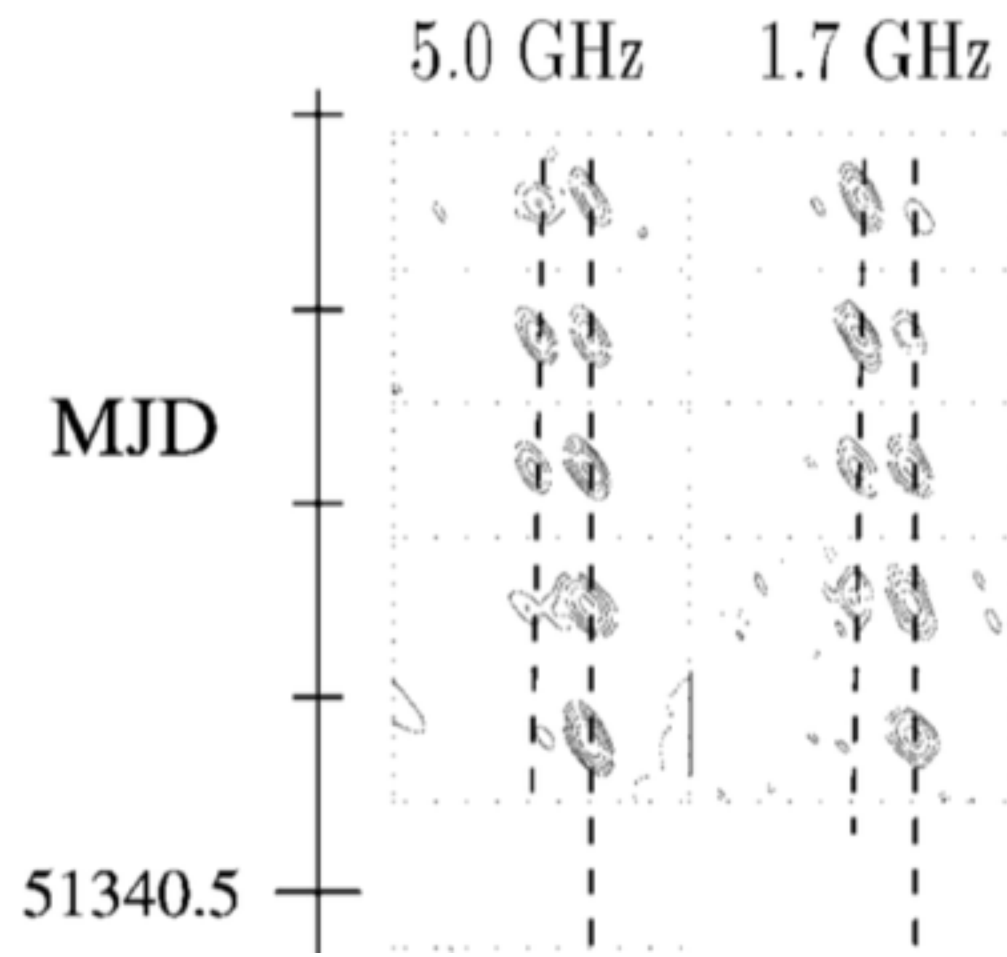


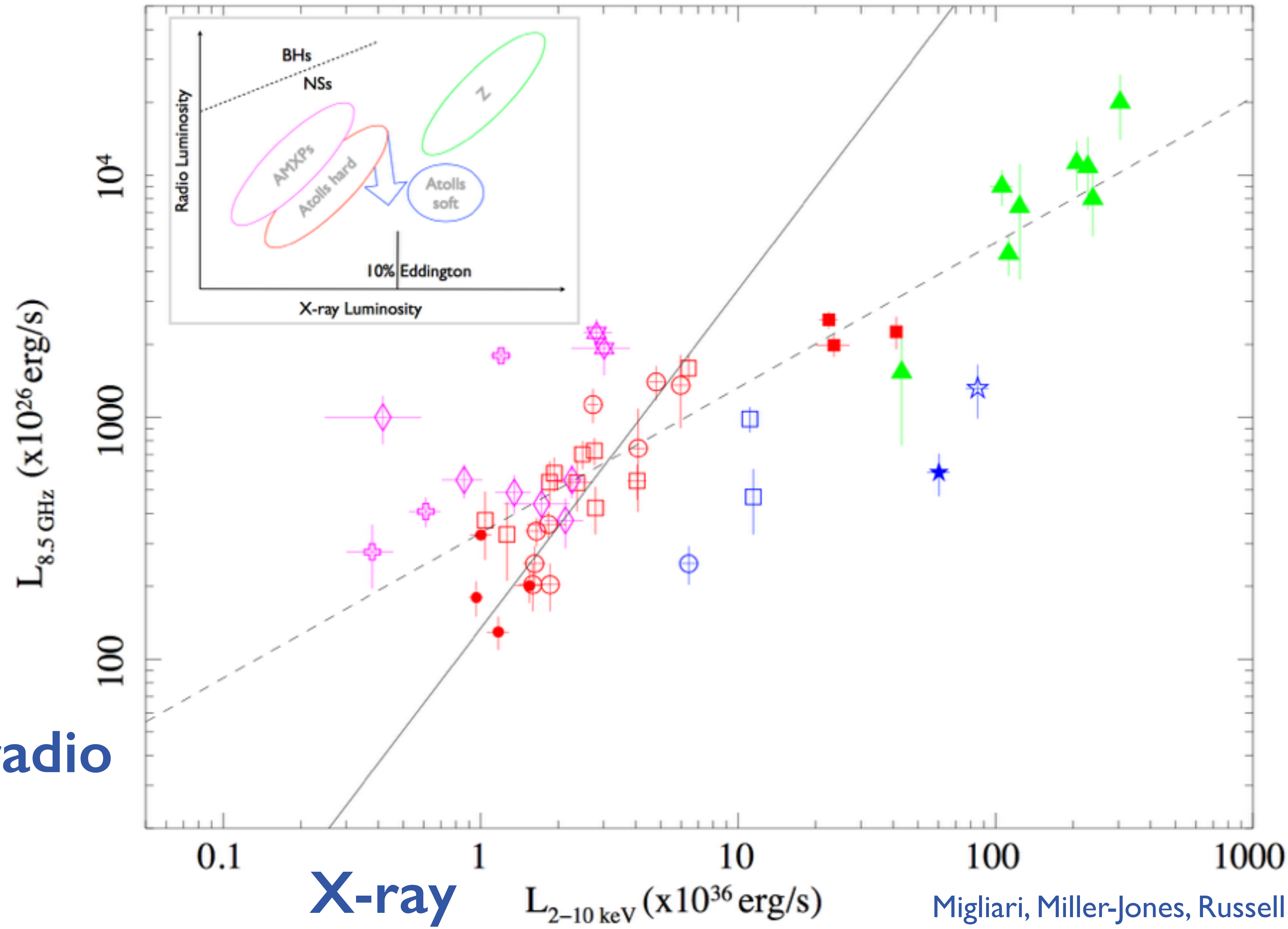
FIG. 1. Brightness distribution of Sco X-1 at 1465 MHz. The contour levels are at −0.8 (dashed), 0.8, 1.6, 3.2, 4.8, 6.4, 8.0, 9.6, 12.8, 16.0, and 19.2 mJy per beam. The full width at half-power beamwidth is shown at upper right.

Sco X-1 : $\Gamma > 3$



Fomalont+ 2001

Jets from neutron stars

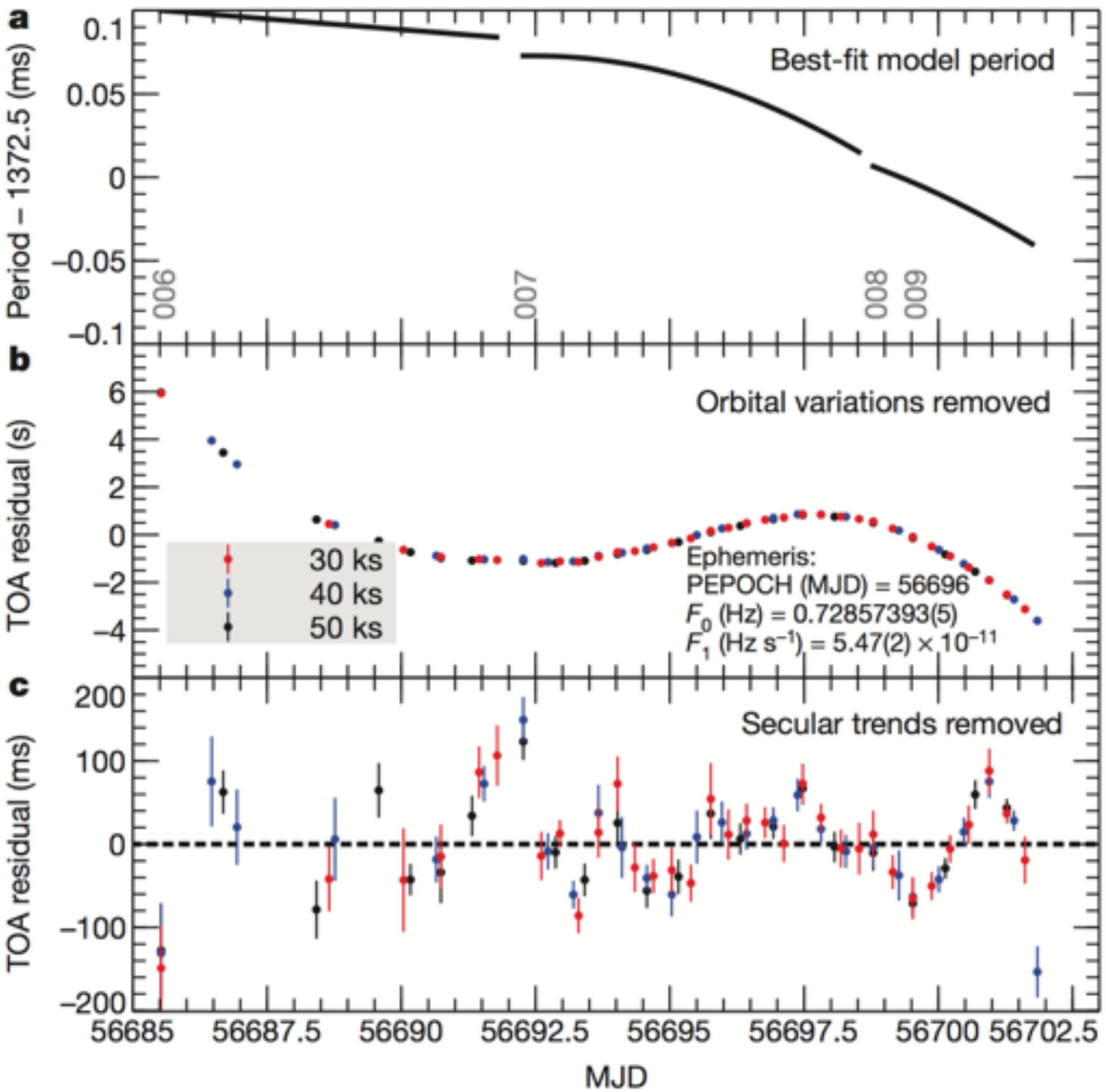


radio

X-ray

Migliari, Miller-Jones, Russell 2011

Ultra-luminous X-ray Source (ULX) pulsars



M82 X-2 Bachetti+ 2014

P = 1.37 s

$\dot{P} \approx -2 \times 10^{-10}\,\mathrm{s\,s^{-1}}$ *strong spin-up*

Timescale: $\dfrac{P}{\dot{P}} \approx 300\,\mathrm{years}$

Two more so far…

NGC 7793 P13 P = 0.43 s

NGC 5907 X-1 P = 1.13 s

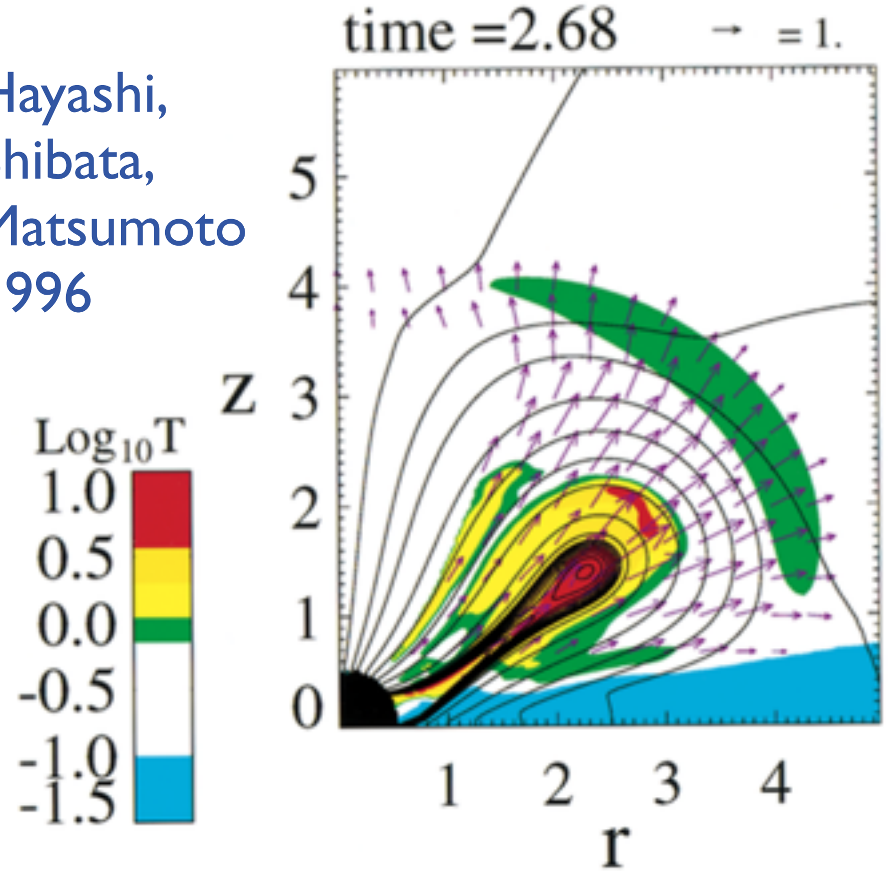
Max pulsed:
$L_X = 5\mathrm{x}10^{39}$ erg/s (3-30 keV)

Chandra (<10 keV) + NuSTAR (pulsed, >10 keV):
$L_X \sim 10^{40}$ erg/s (0.5-30 keV)

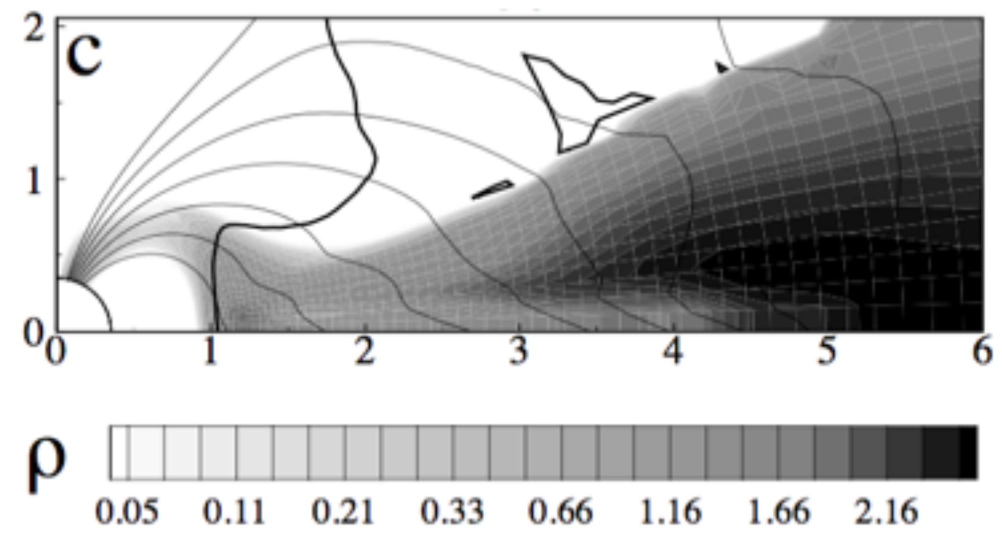
Non-relativistic MHD simulations

opening + reconnection: flaring

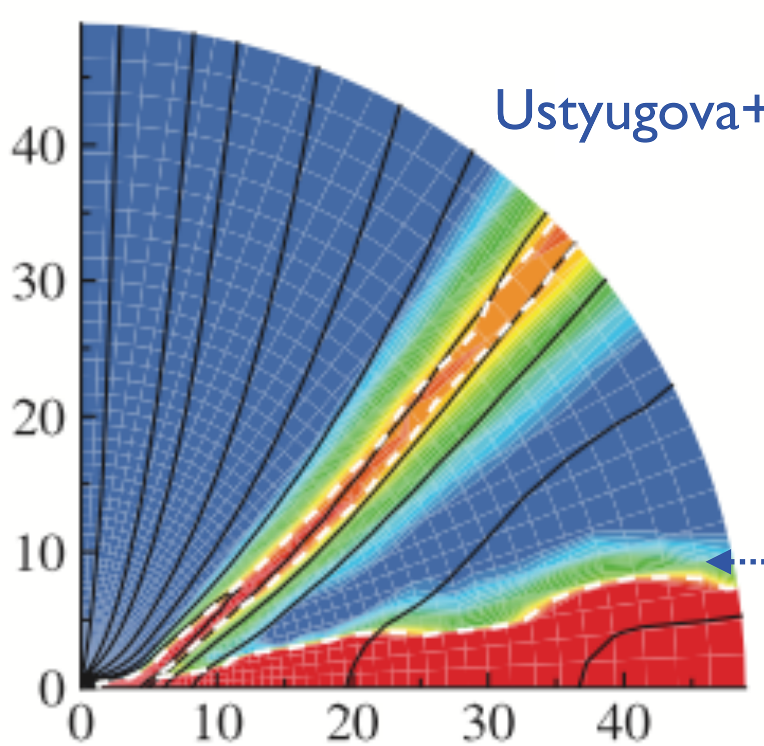
Hayashi, Shibata, Matsumoto 1996



funnel flows & accretion torque



Romanova+ 2002

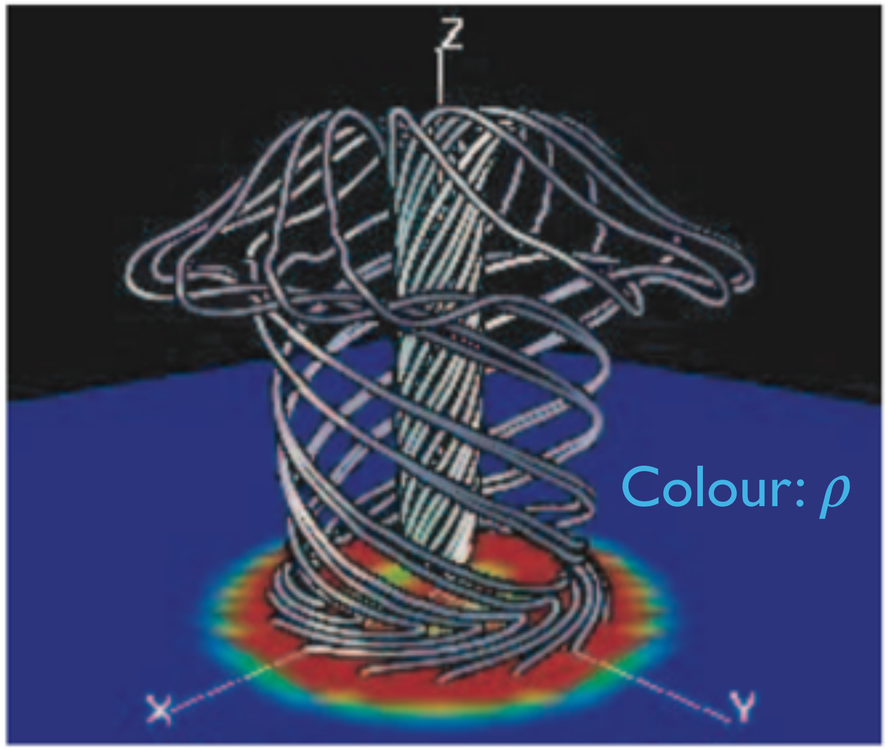


Ustyugova+ 2006

axial magnetised jet

β = 1 contour

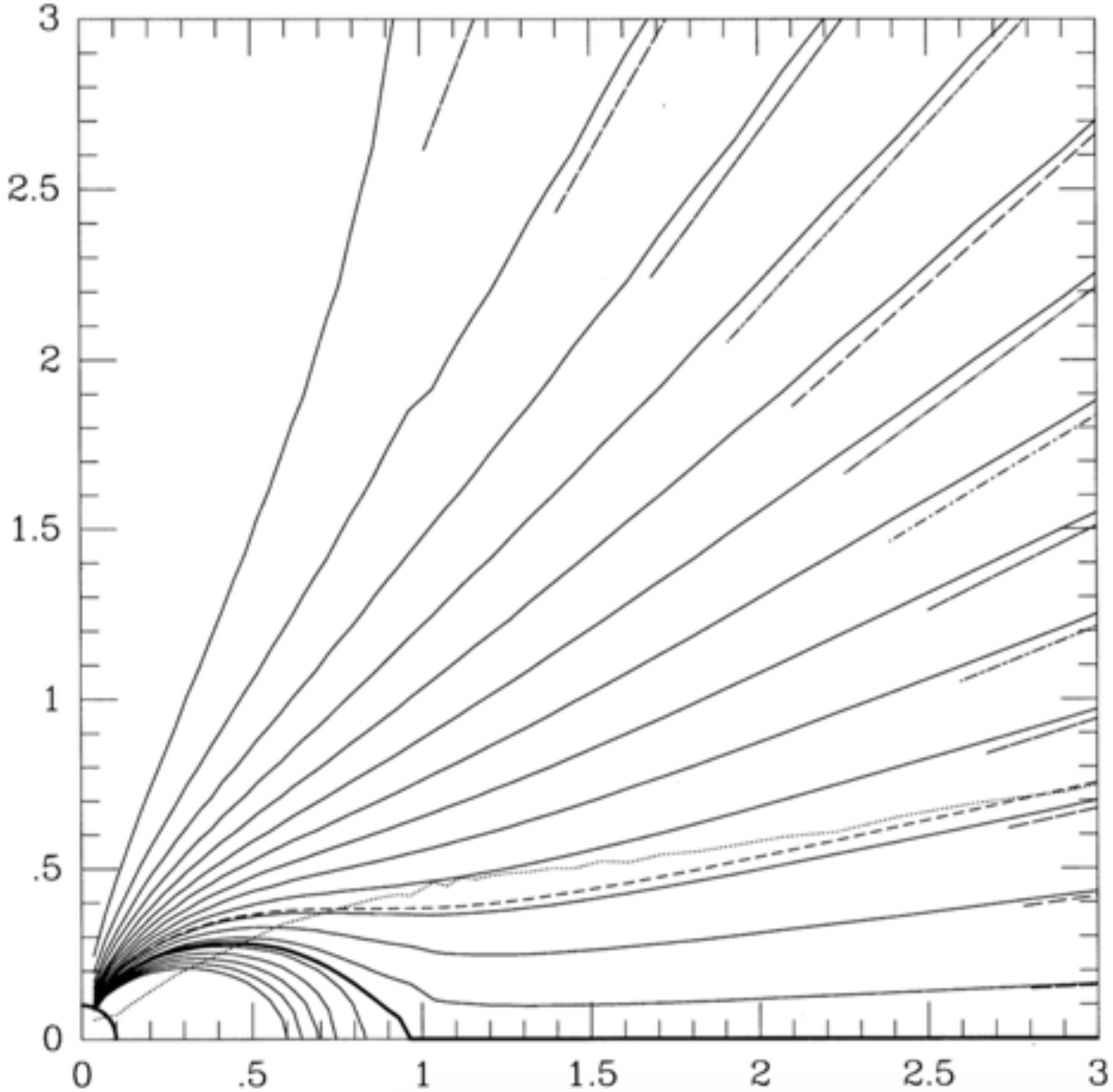
Colour: plasma β



Colour: ρ

Kato, Hayashi, Matsumoto 2004

Isolated Pulsars 101



Contontopoulos, Kazanas, Fendt 1999

Steady-state solution of Grad-Shafranov equation

Aligned axes: $\chi = 0$

Spin-down luminosity

$$L = \frac{\mu^2 \Omega^4}{c^3} \left(1 + \sin^2 \chi\right)$$

$$\approx \frac{2}{3c} \Omega^2 \psi^2_{\mathrm{open},0}$$

Gruzinov 2005, Spitkovsky 2006

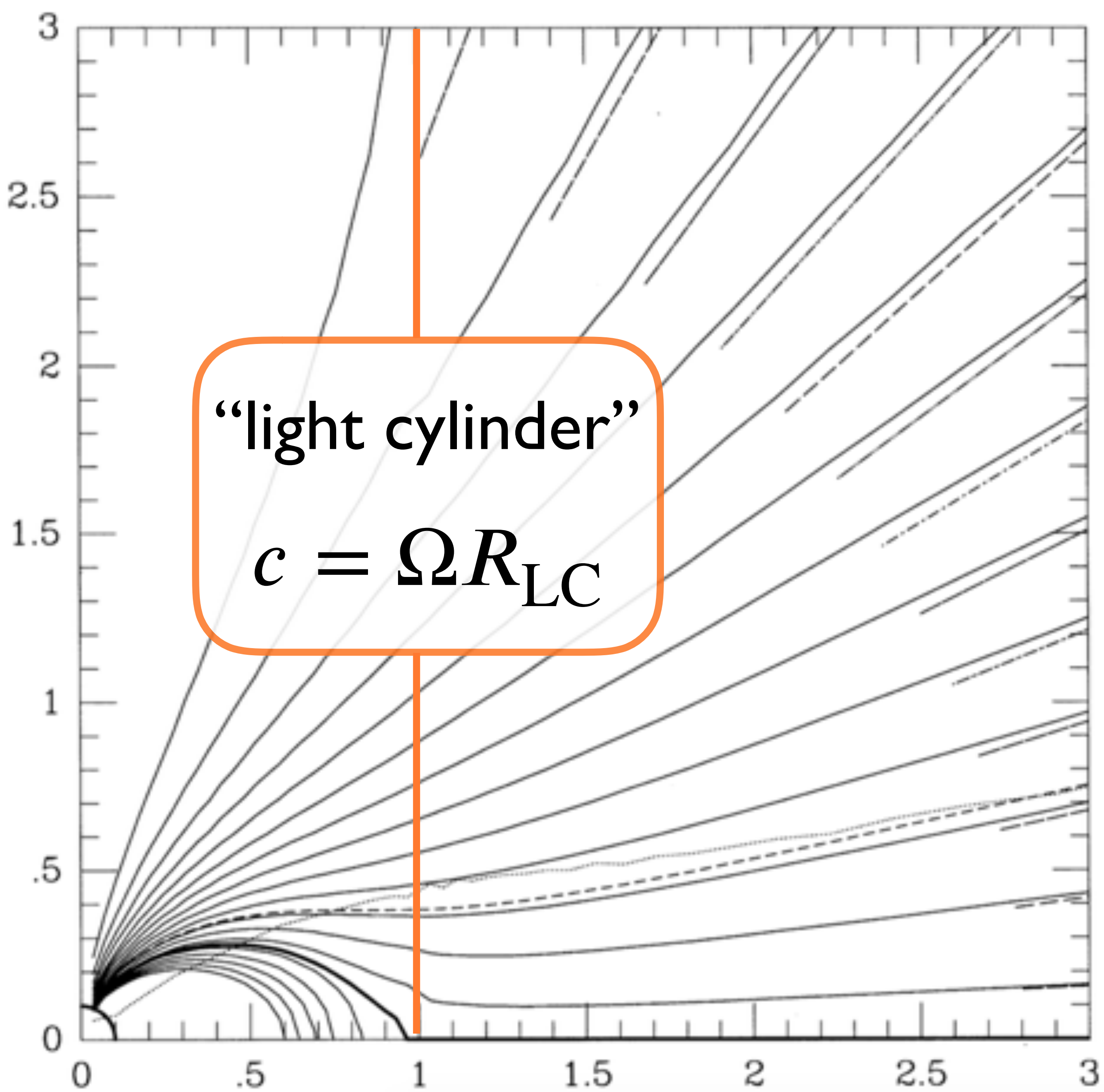
Contopoulos 2005

torque: $N = -L/\Omega$

where

$$L = \int_{\mathrm{surface}} \frac{\boldsymbol{E} \times \boldsymbol{B}}{4\pi} \cdot d\boldsymbol{S}$$

Isolated Pulsars 101



Contopoulos, Kazanas, Fendt 1999

Aligned axes

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Contopoulos 2005

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where

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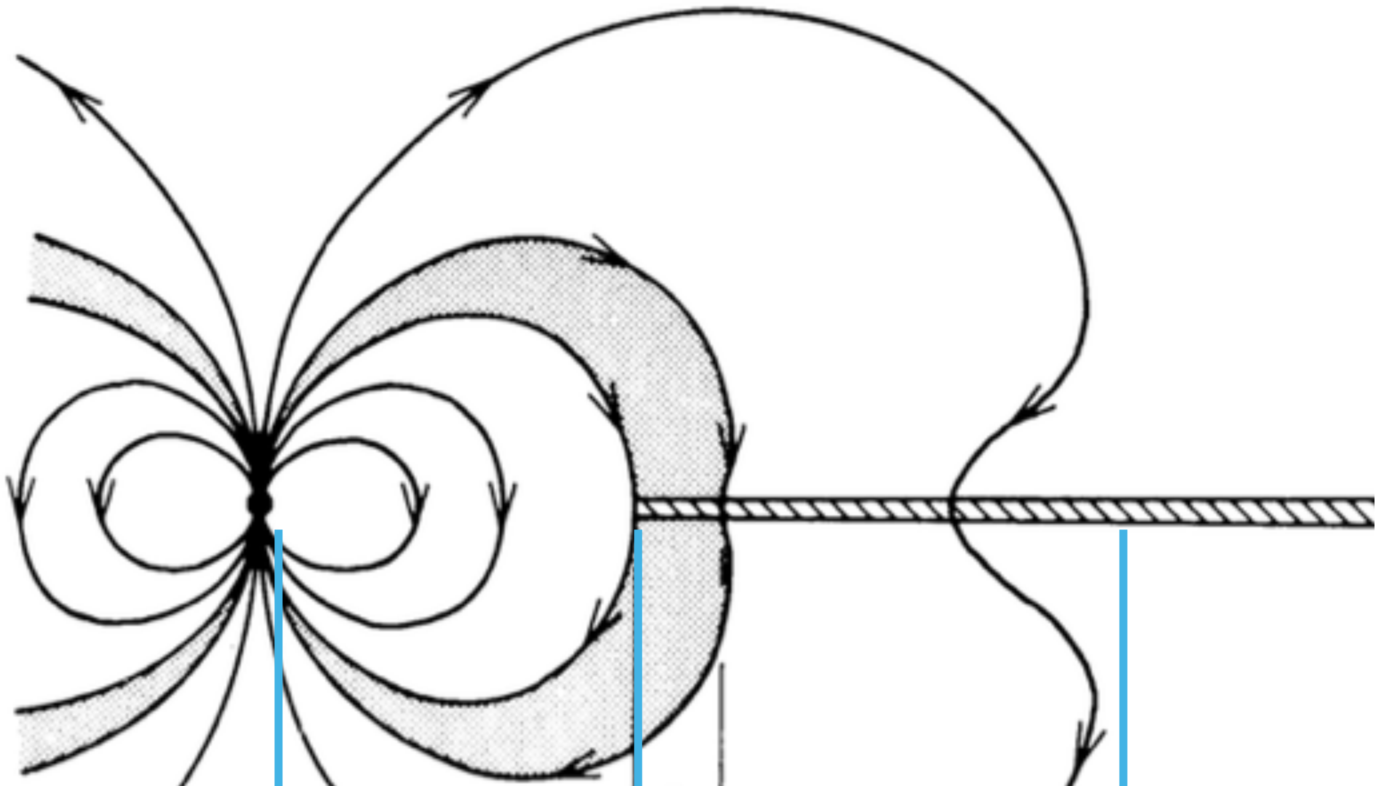
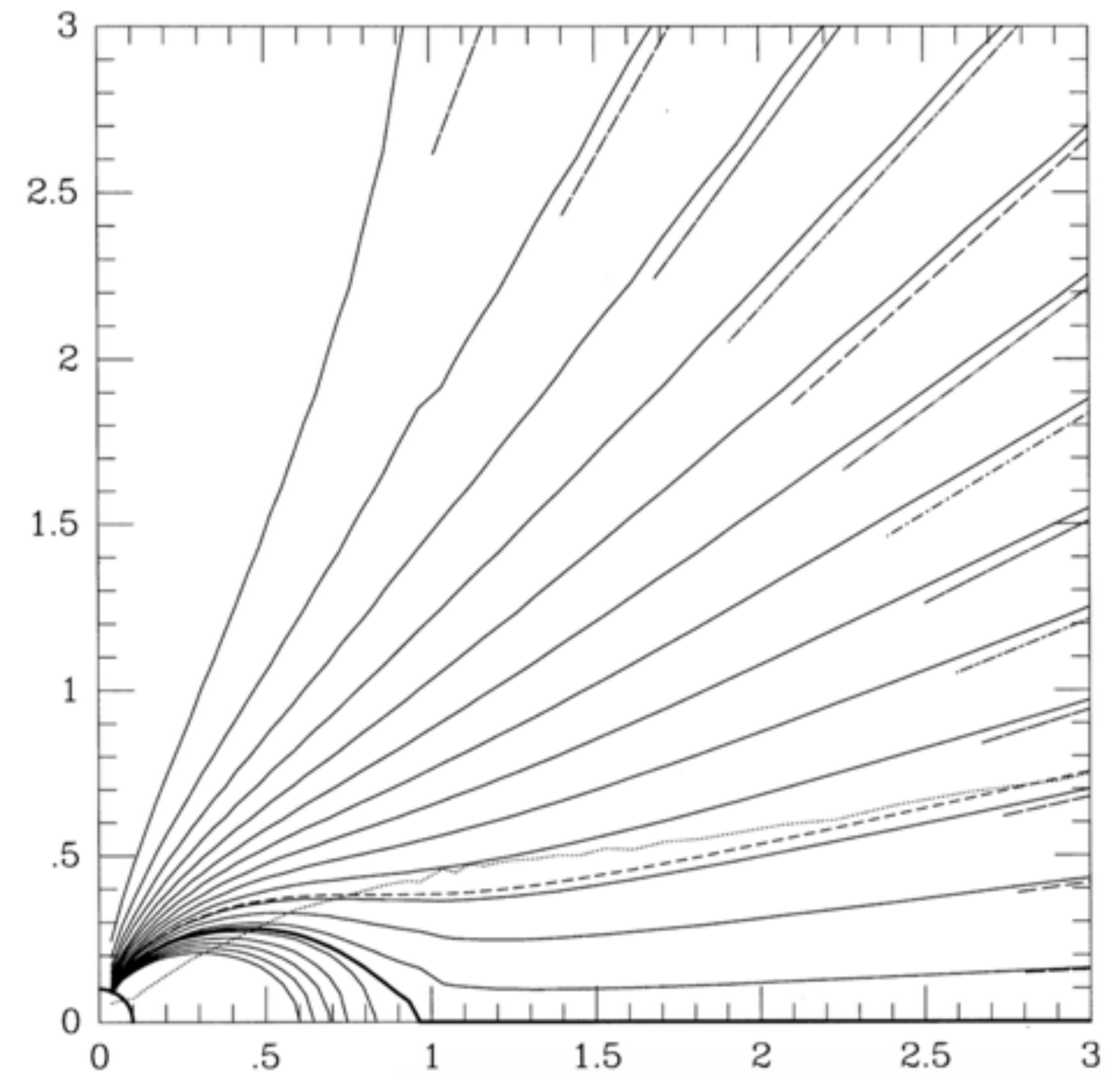
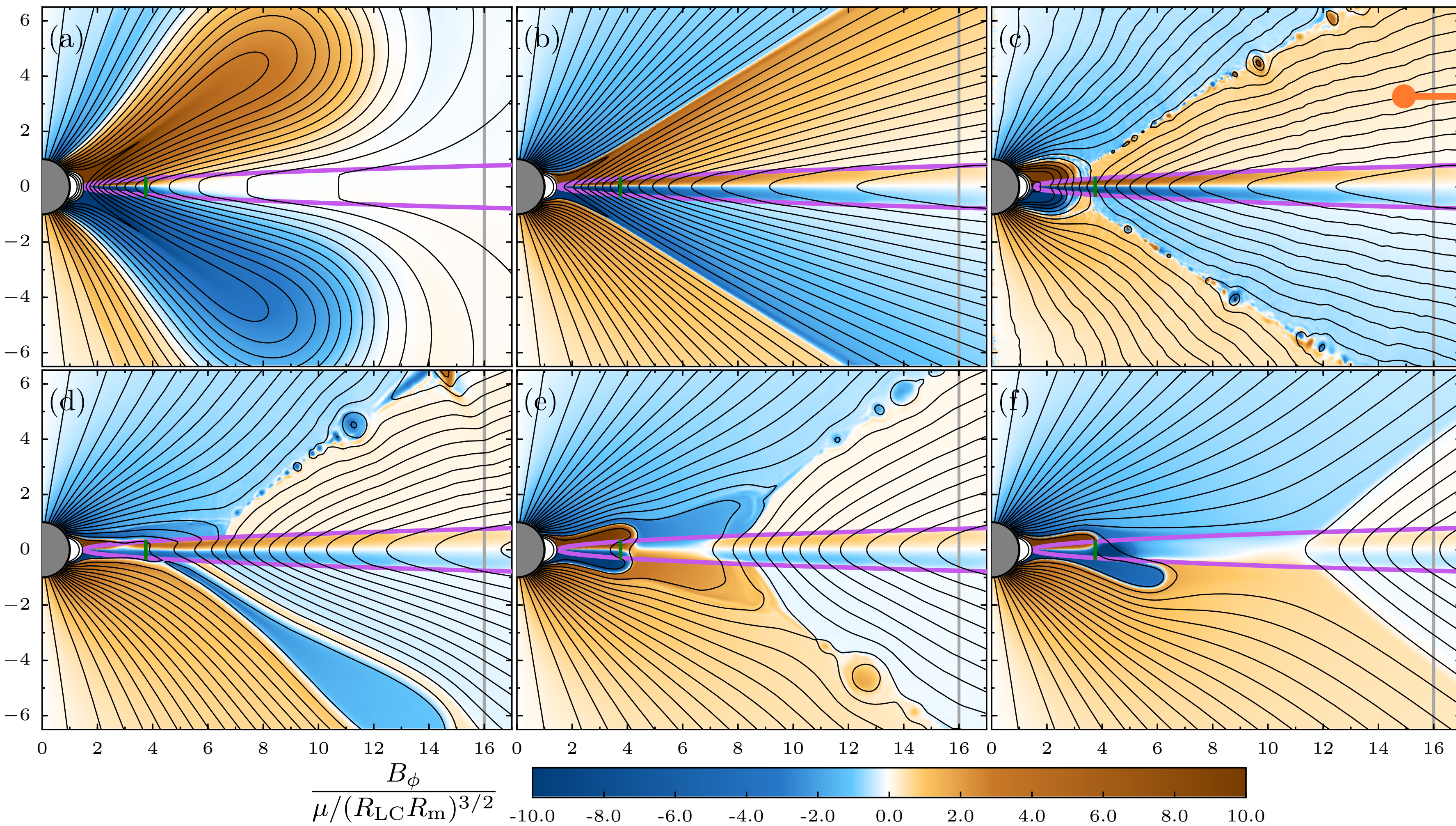
Important radii





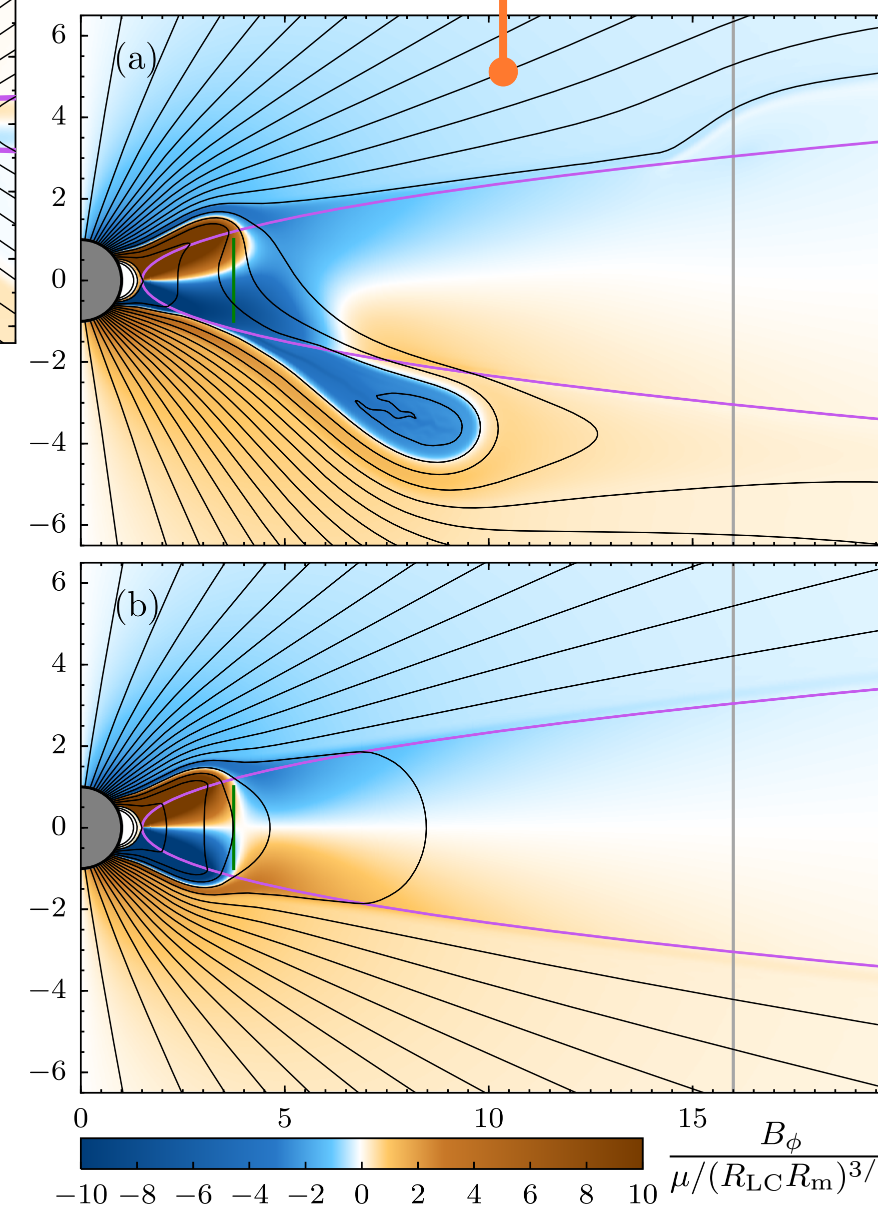
r_{star}	r_{m}	r_{co}	r_{LC}
stellar	magnetospheric	corotation	light cylinder

Relativistic magnetosphere + disc simulations



thin discs

thick discs



Parfrey, Spitkovsky, Beloborodov 2017

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

Self-consistent disc physics + relativity

Demands / wish list

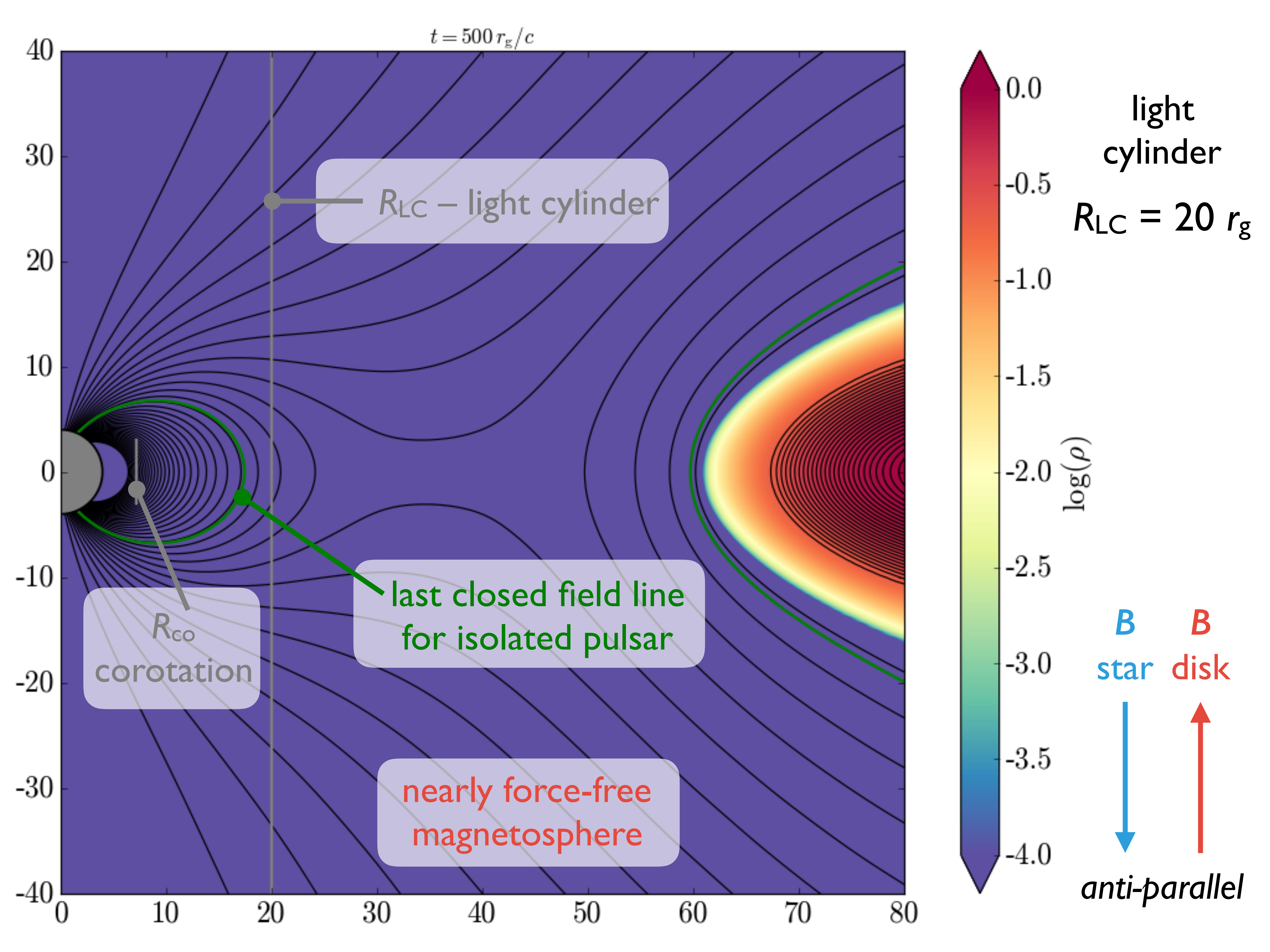
1. Evolve the coupled disc–magnetosphere system self-consistently
2. Accreting material initially entirely outside light cylinder
3. General relativity (fixed spacetime) — Kerr metric
4. Very high magnetization in nearly force-free magnetosphere

GRMHD simulations with HARM code

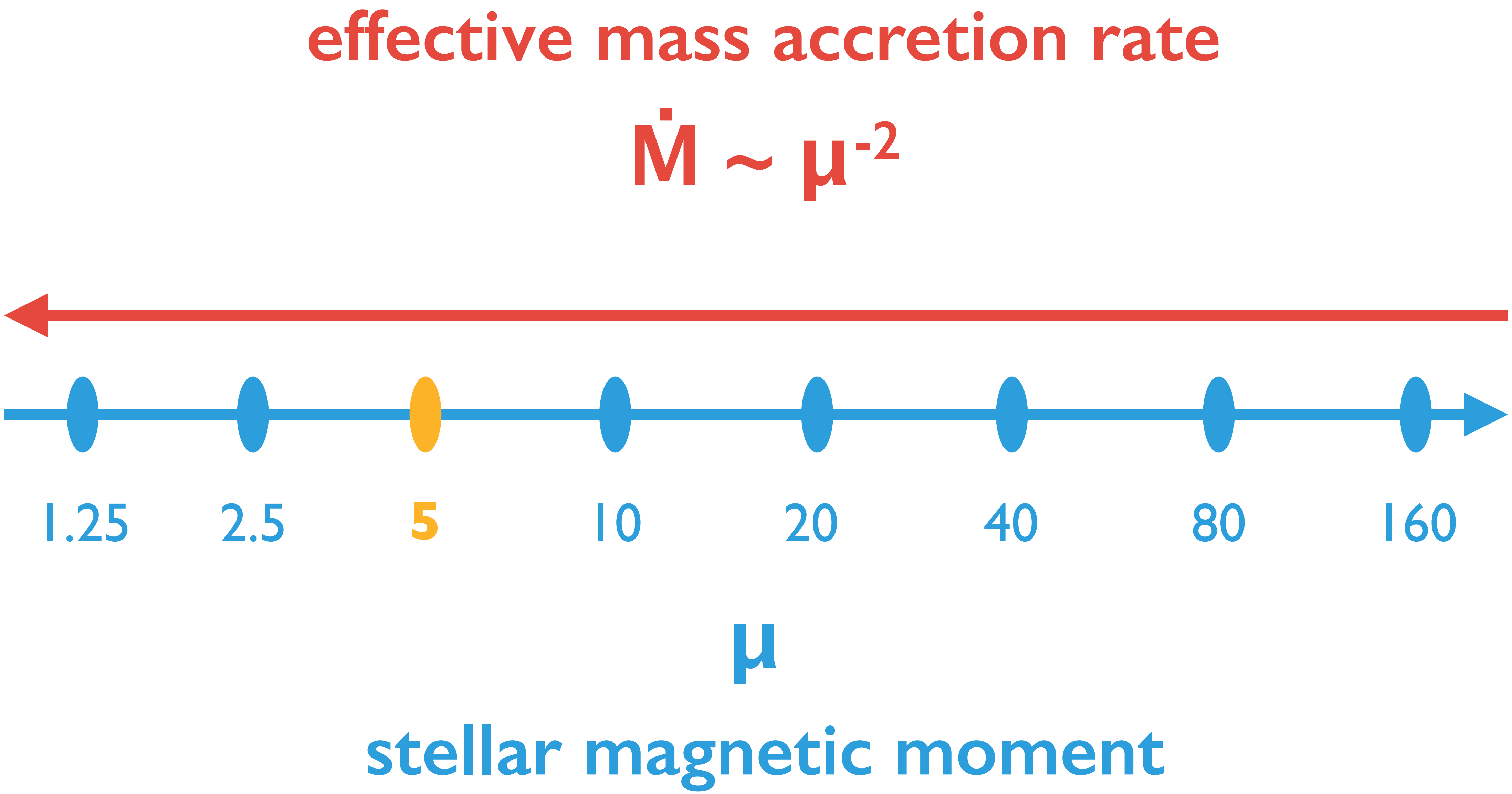
Gammie, McKinney, Toth 2003, Noble + 2006

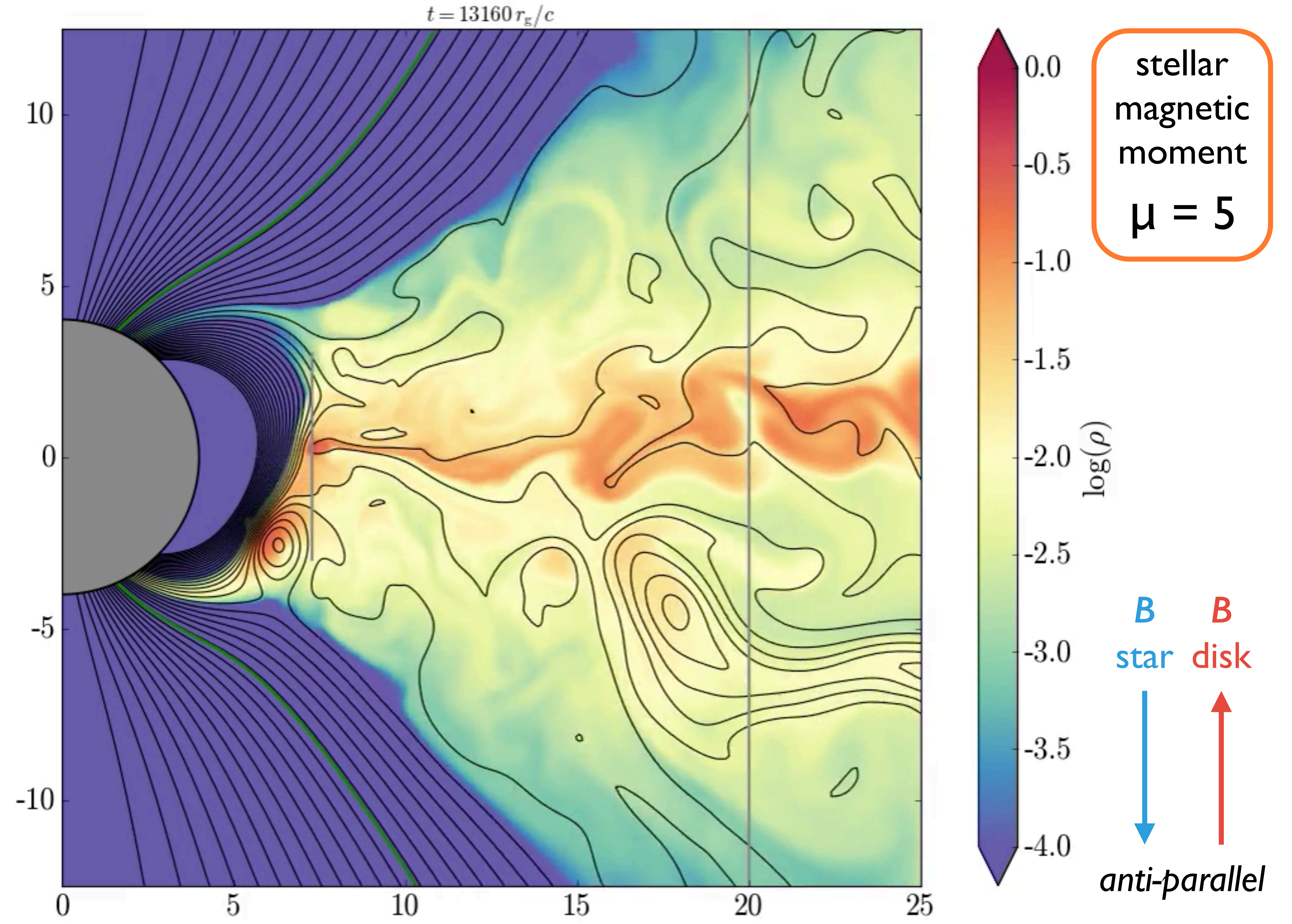
Simulation properties

1. Total-energy conserving — i.e. include shock heating
2. Relativistic-gas EOS
3. Large-scale poloidal magnetic flux in accretion flow



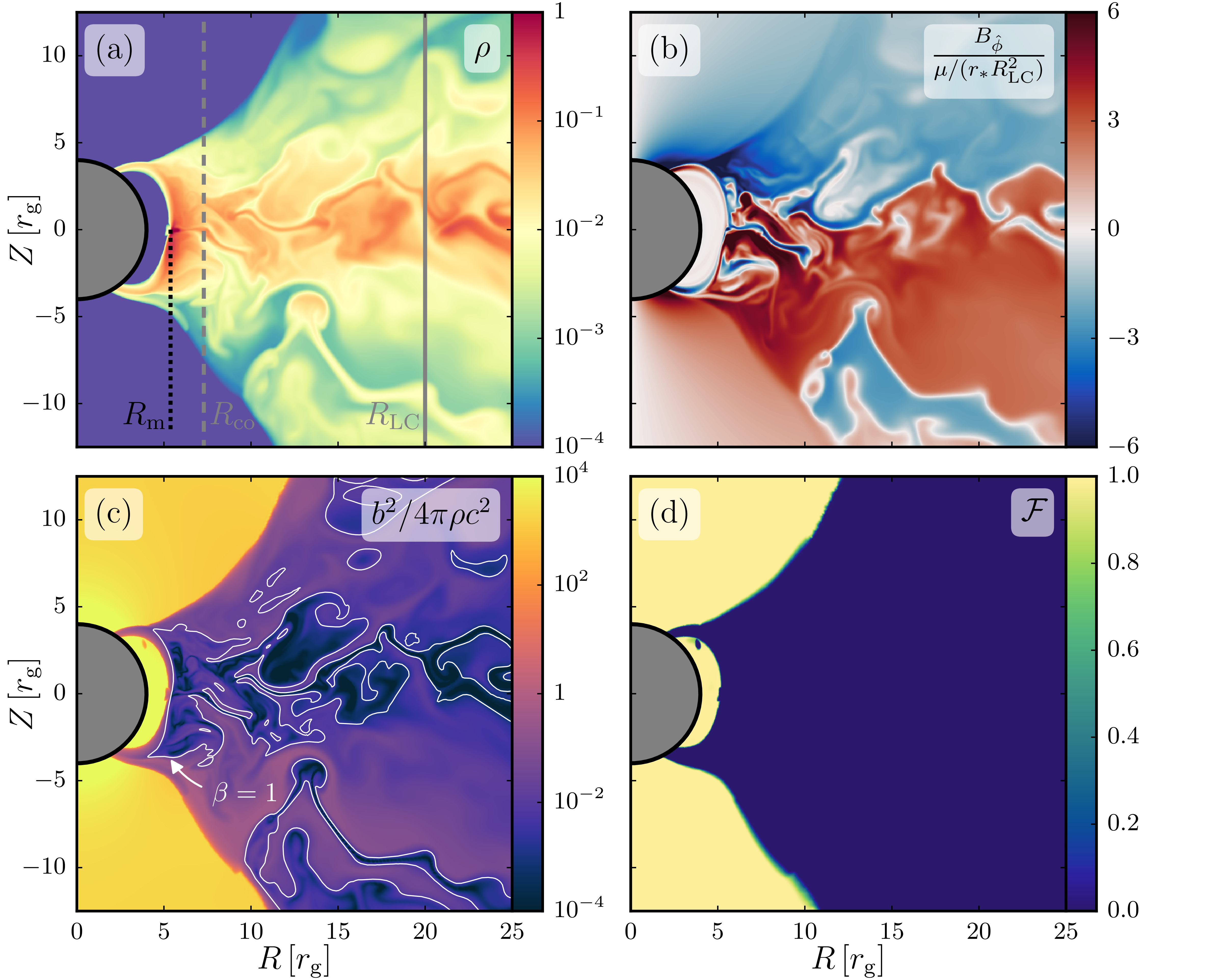
$t = 500\, r_g/c$
R_{LC} – light cylinder
R_{co}
corotation
last closed field line
for isolated pulsar
nearly force-free
magnetosphere
$\log(\rho)$
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
light
cylinder
$R_{LC} = 20\ r_g$
B star
B disk
anti-parallel

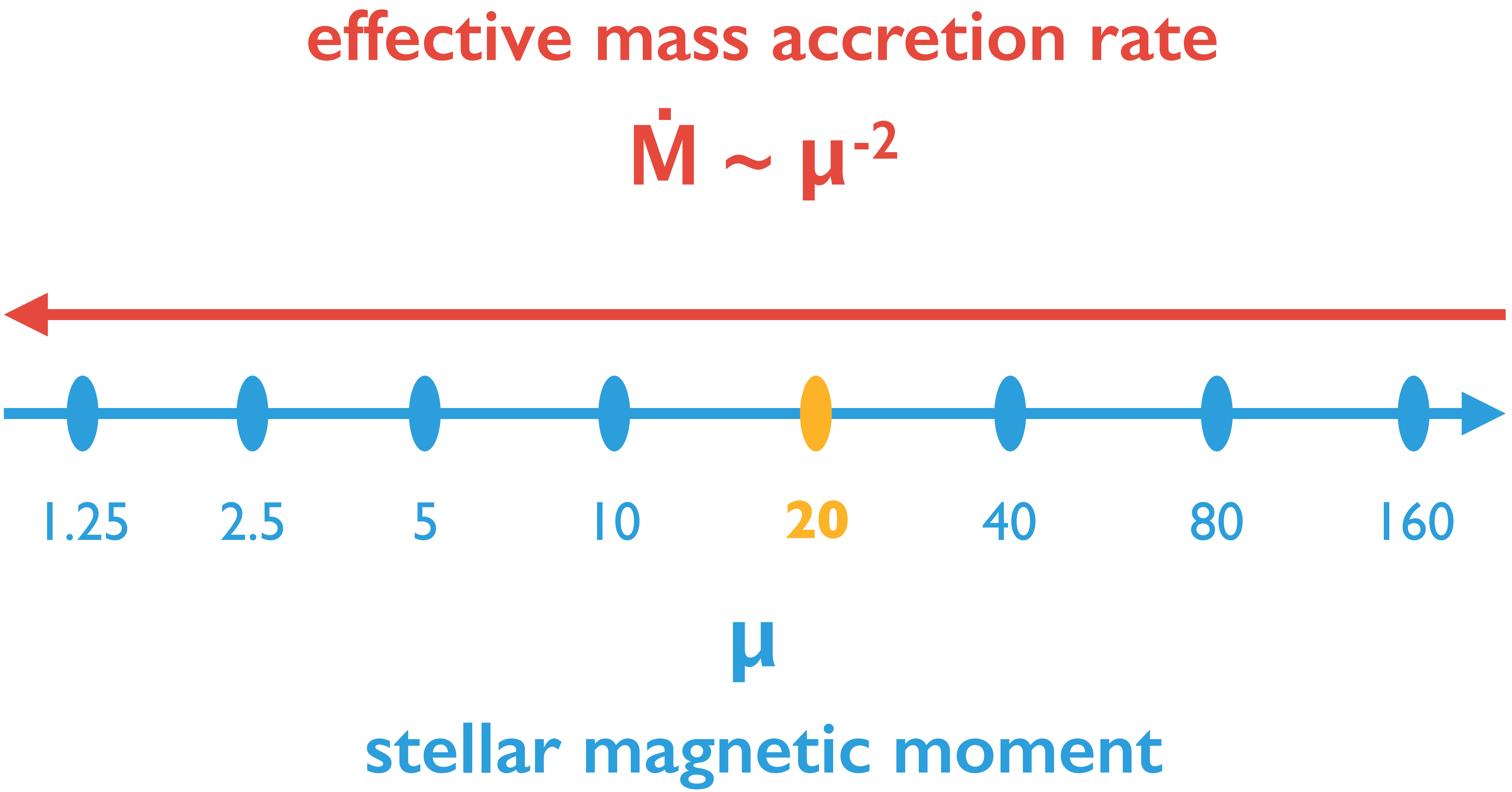

effective mass accretion rate
Ṁ ~ μ-2
1.25
2.5
5
10
20
40
80
160
μ
stellar magnetic moment

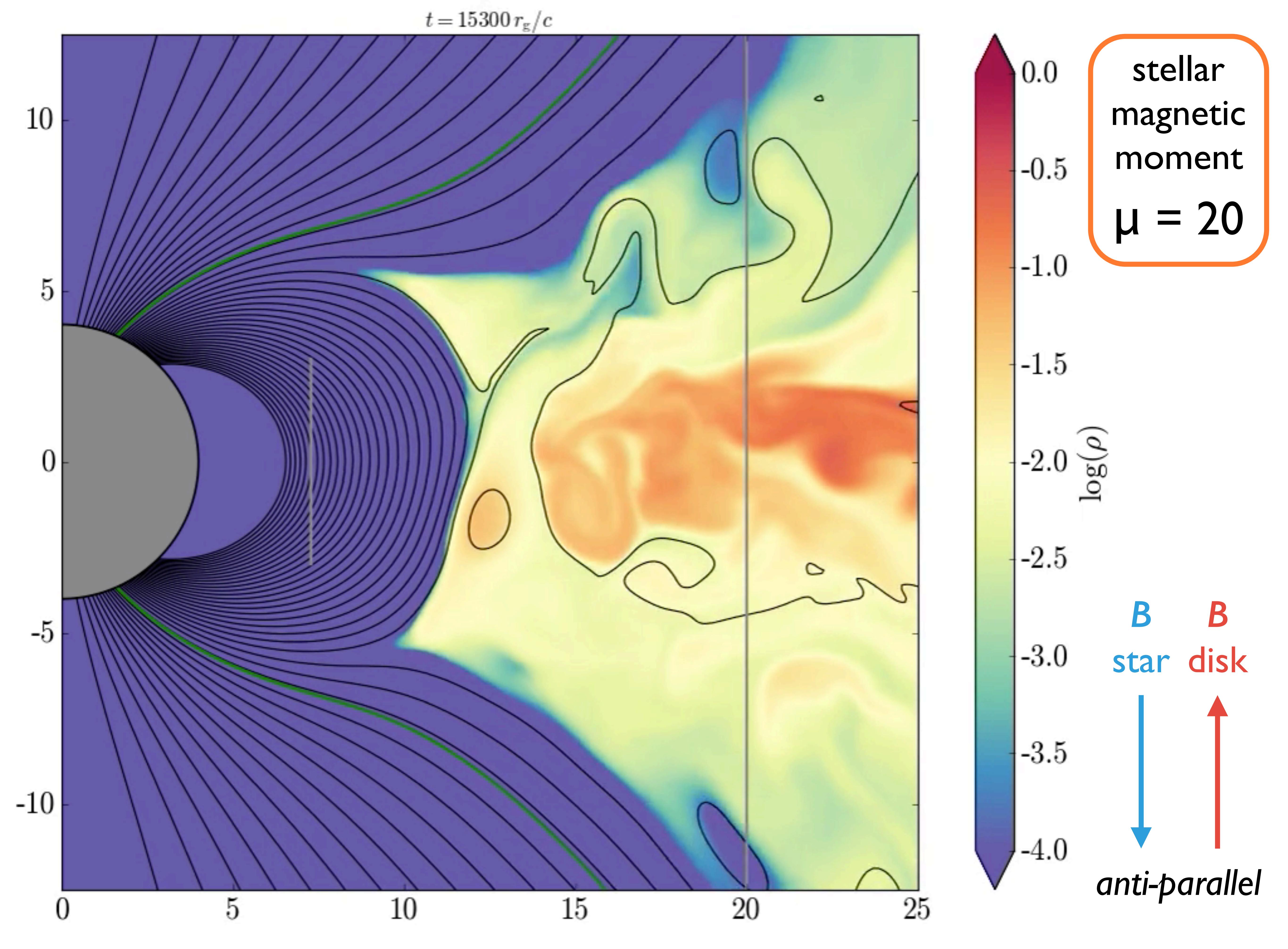


$t = 13160\, r_g/c$
$\log(\rho)$
stellar magnetic moment
μ = 5
B star
B disk
anti-parallel

Parfrey & Tchekhovskoy 2017



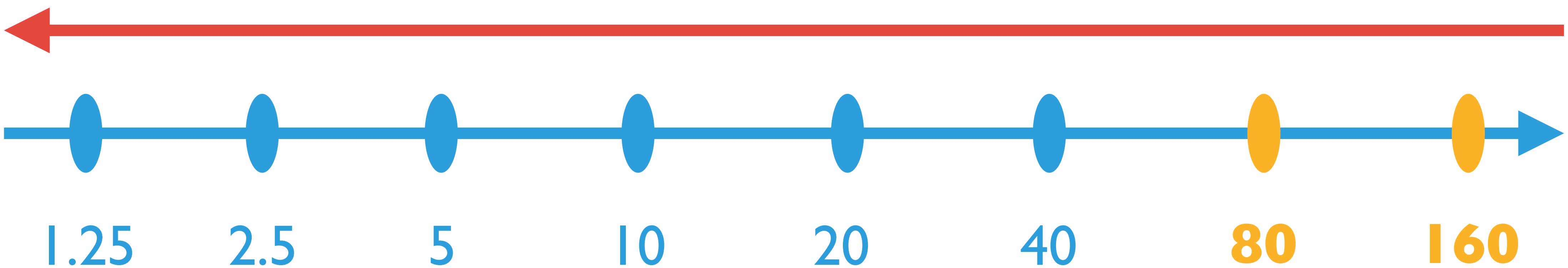

effective mass accretion rate
$\dot{M} \sim \mu^{-2}$
1.25
2.5
5
10
20
40
80
160
μ
stellar magnetic moment



$t = 15300\, r_g/c$
log(ρ)
stellar magnetic moment
μ = 20
B star
B disk
anti-parallel

effective mass accretion rate

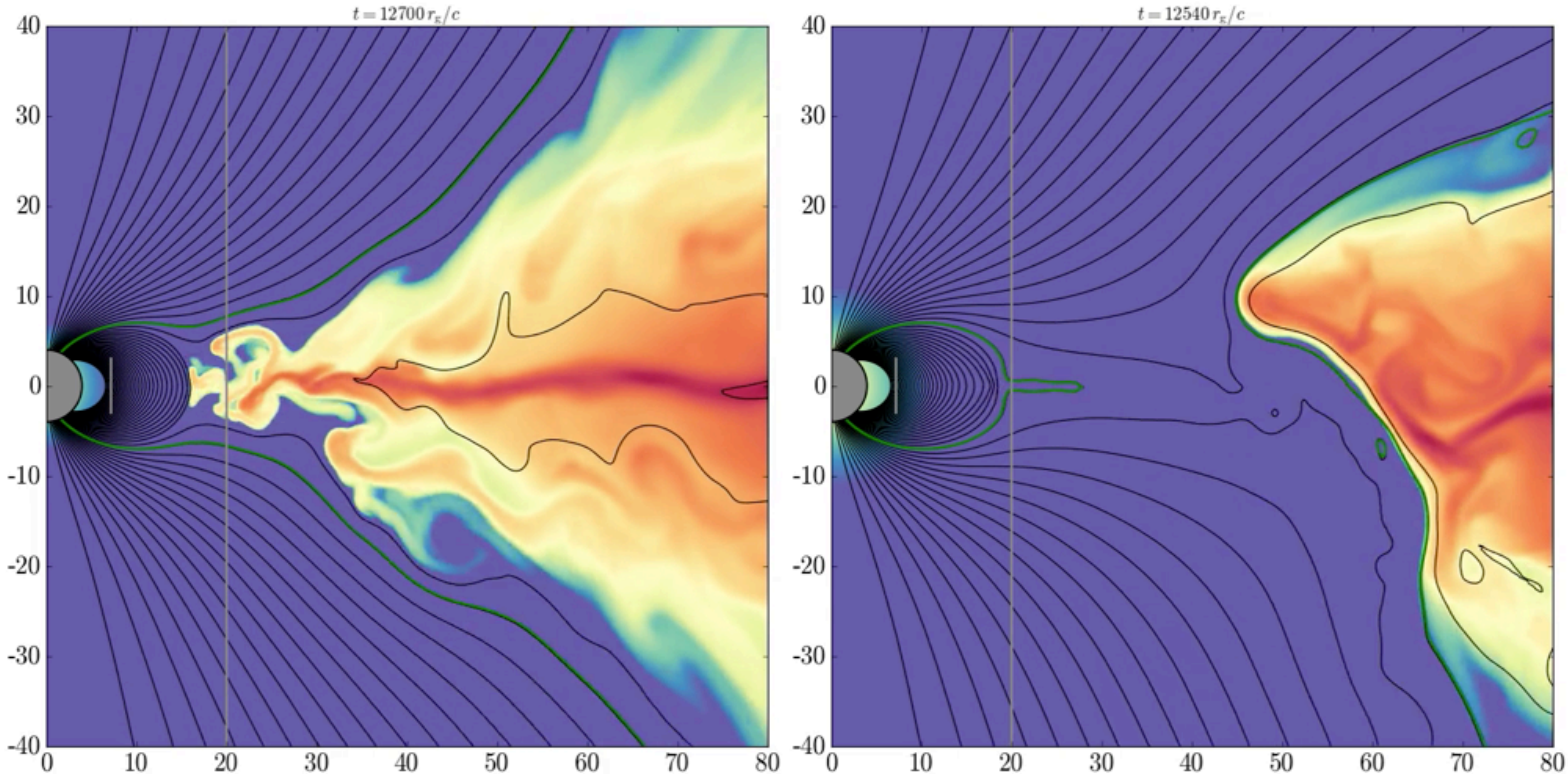
$$\dot{M} \sim \mu^{-2}$$



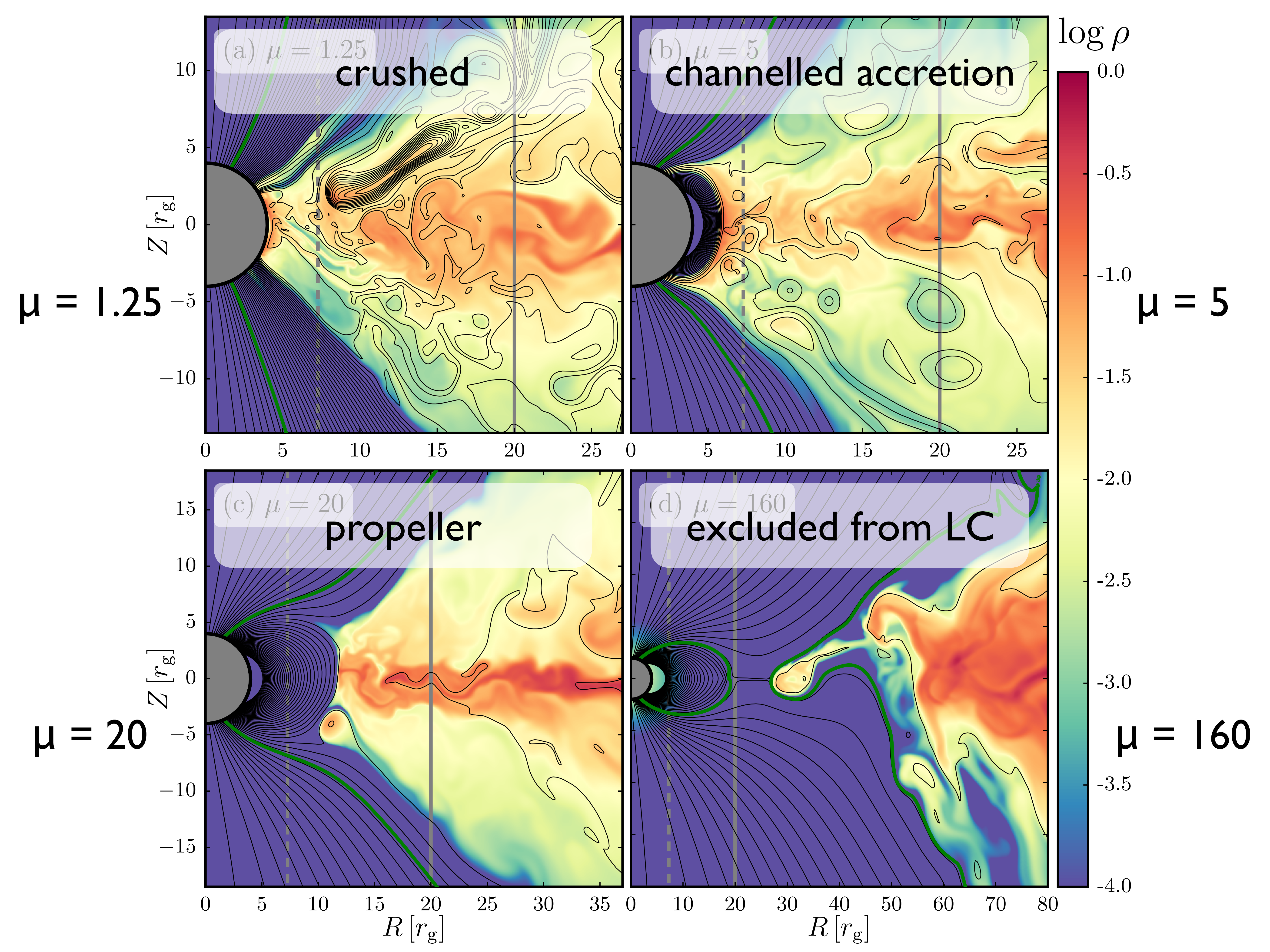
μ

stellar magnetic moment

μ = 80 μ = 160

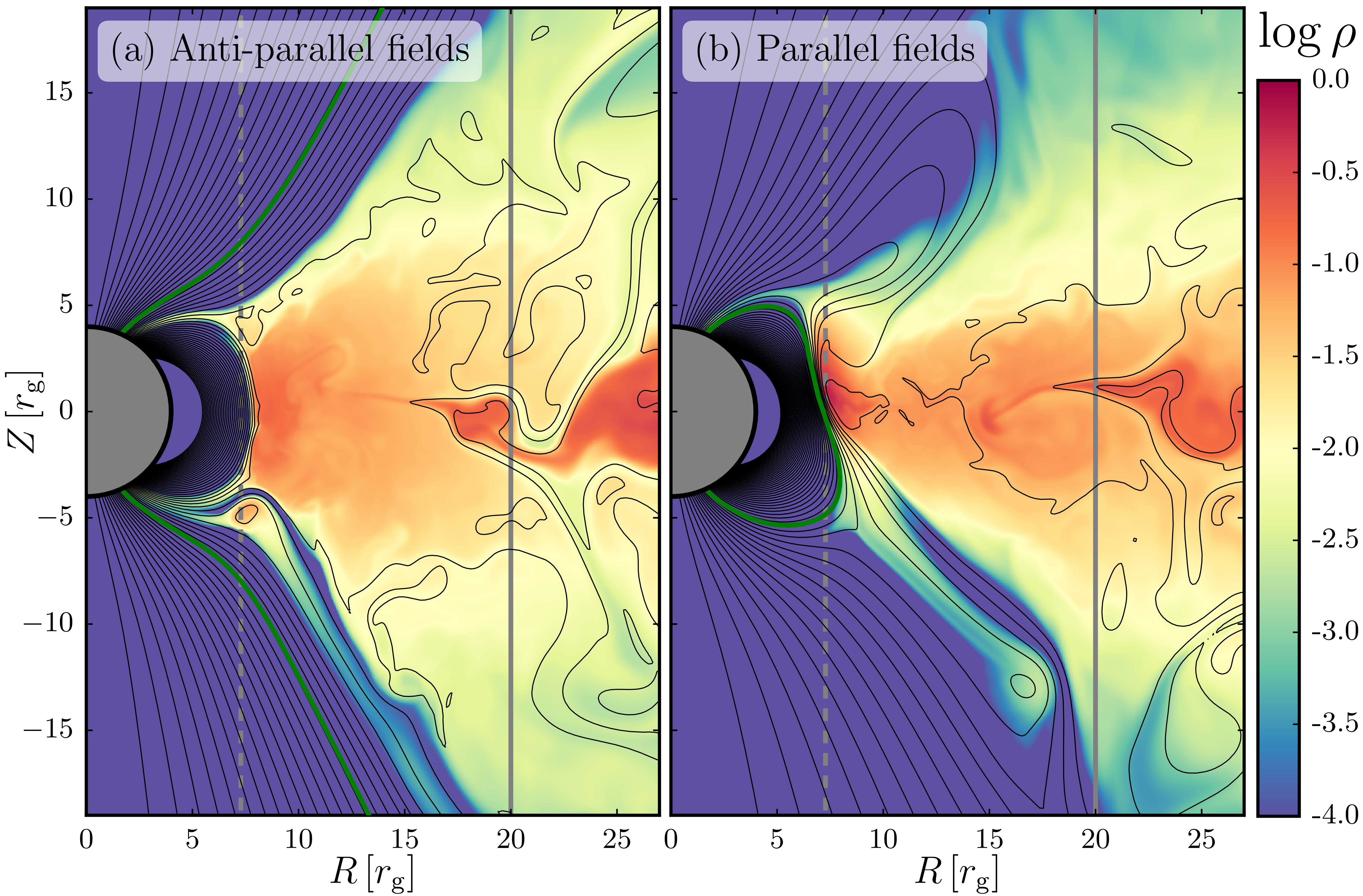


$t = 12700\, r_g/c$
$t = 12540\, r_g/c$
40
30
20
10
0
-10
-20
-30
-40
0
10
20
30
40
50
60
70
80



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

Star–torus field orientation effect



Average values of:

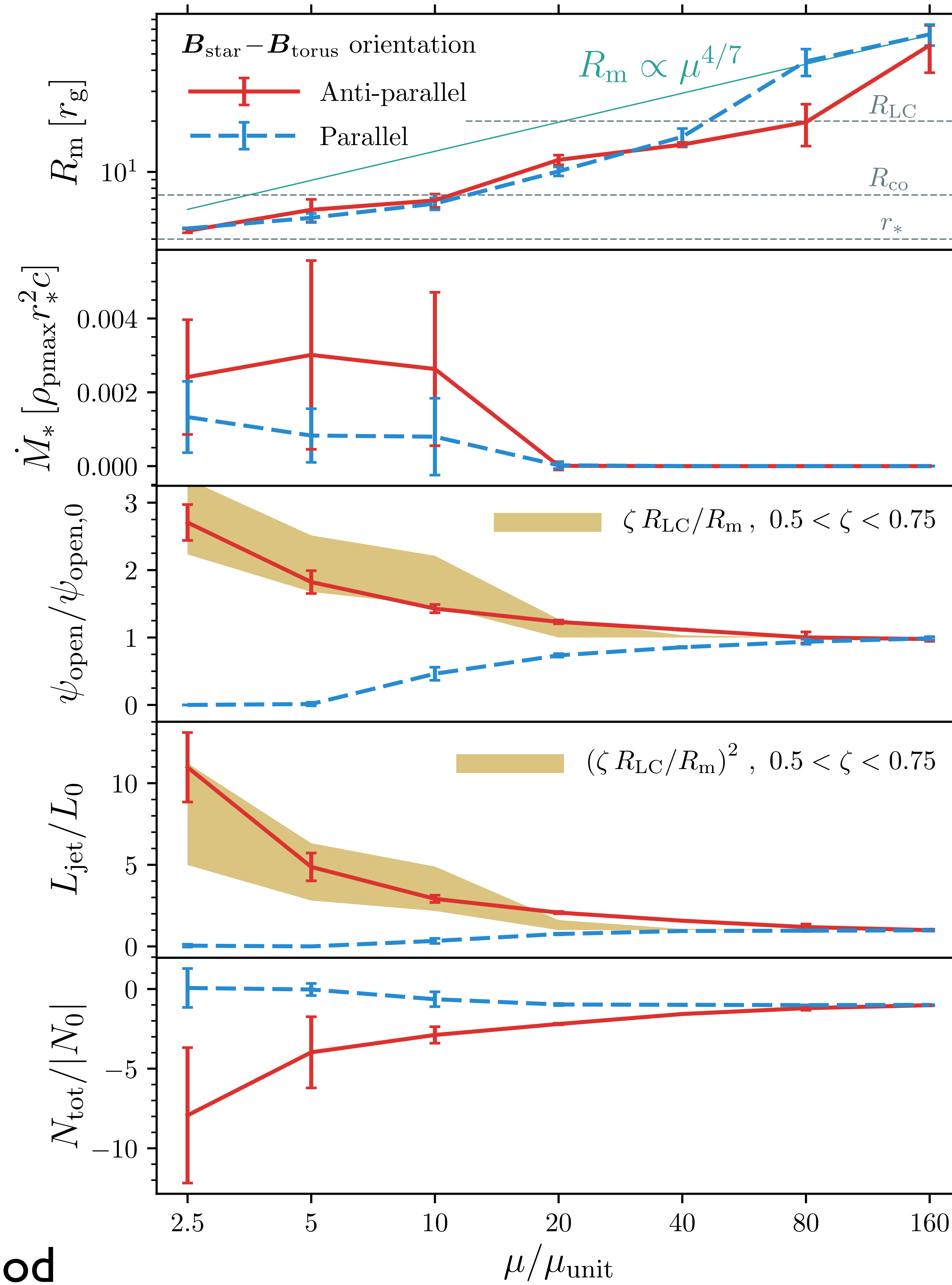
magnetospheric radius

accretion rate

open flux

jet power

stellar torque



Parfrey & Tchekhovskoy 2017

vertical bars: standard deviation over averaging period

Average values of:

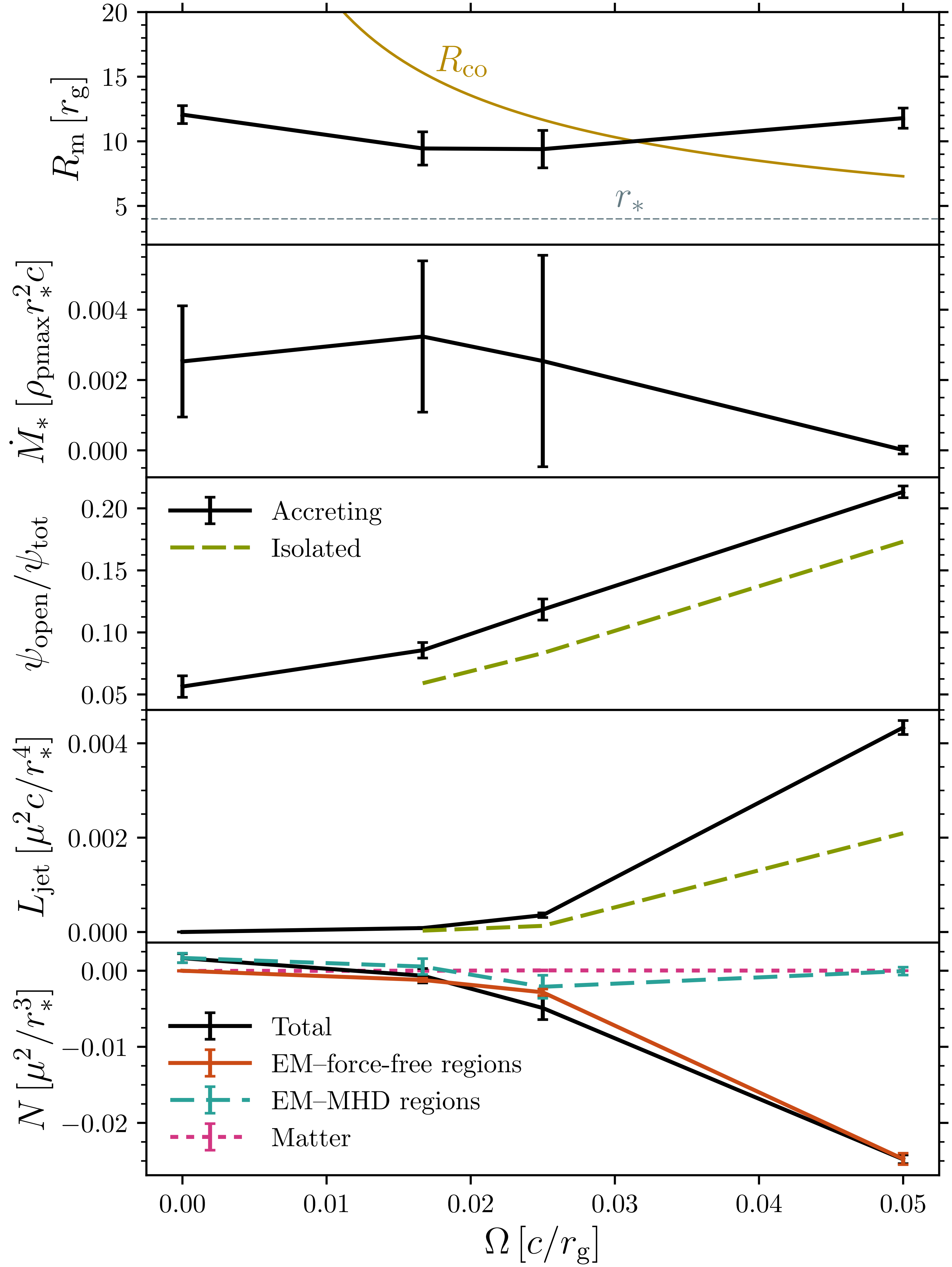
magnetospheric radius

accretion rate

open flux

jet power

stellar torque

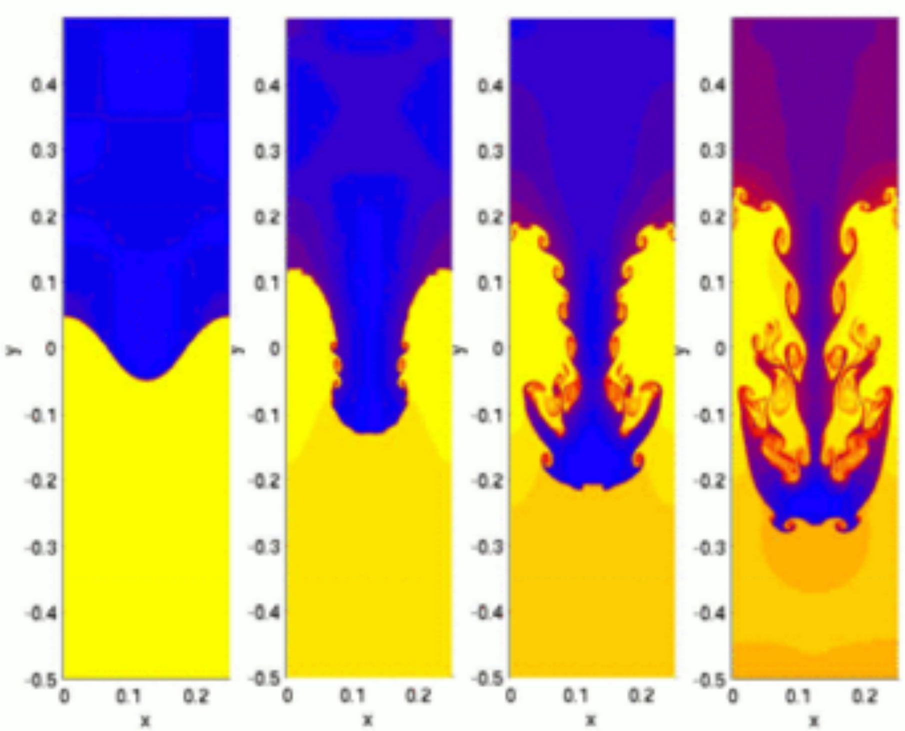


Parfrey & Tchekhovskoy 2017

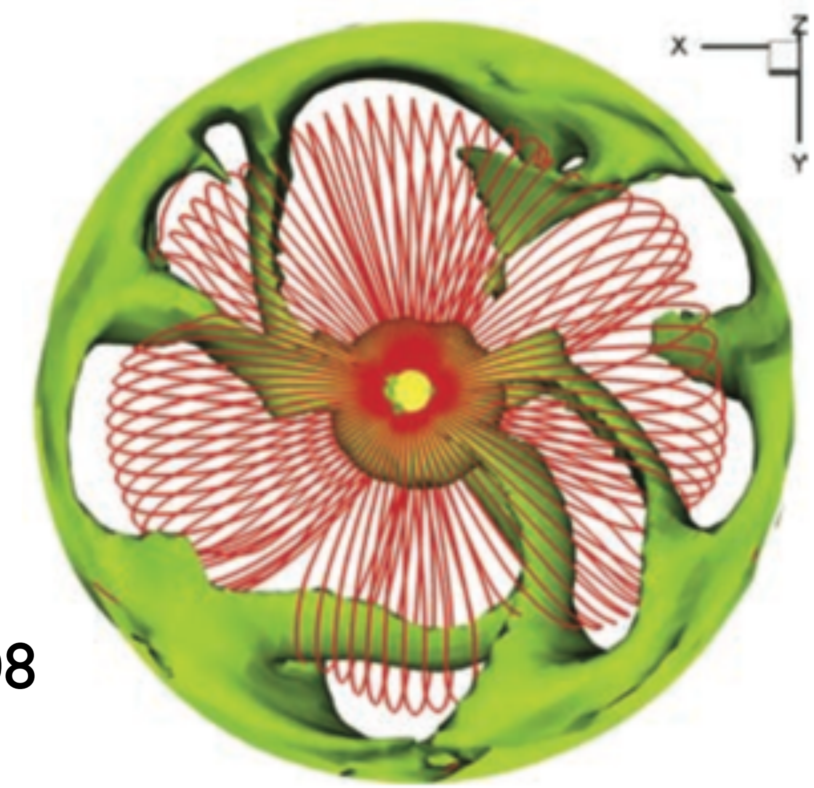
vertical bars: standard deviation over averaging peric

Preliminary: 3D simulations

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

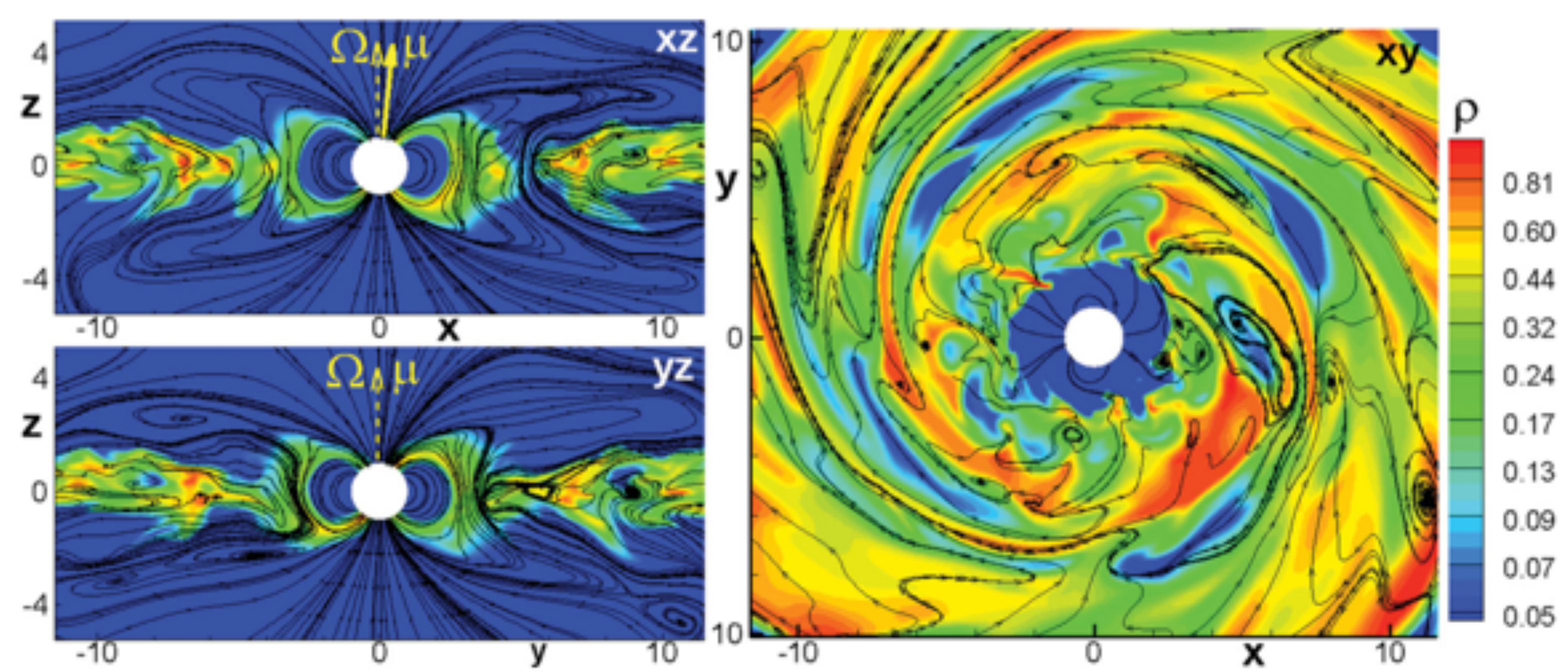


Magnetic Rayleigh-Taylor / Interchange



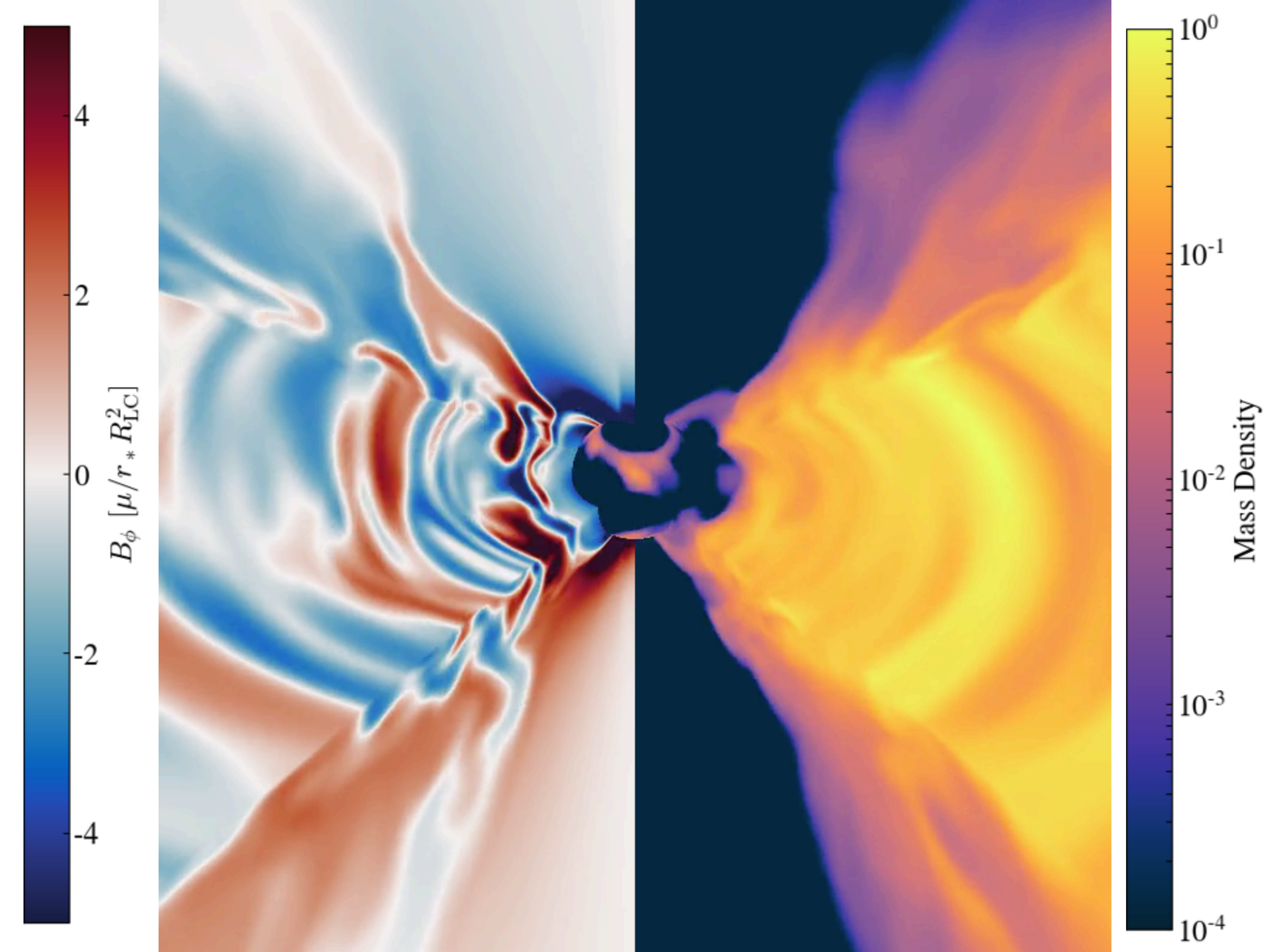
alpha-prescription resistive MHD

Kulkarni & Romanova 2008



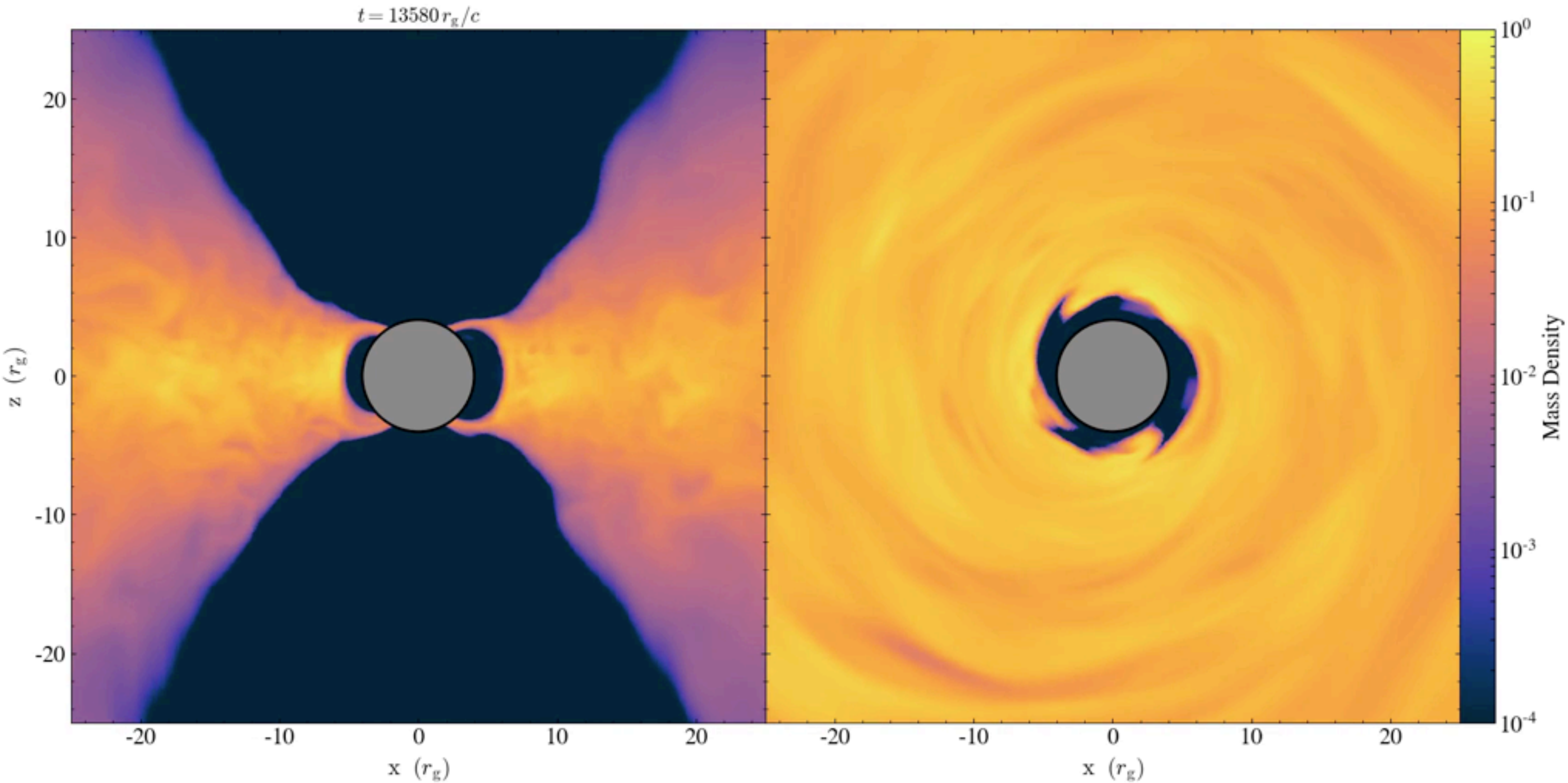
Ideal MHD/MRI disc

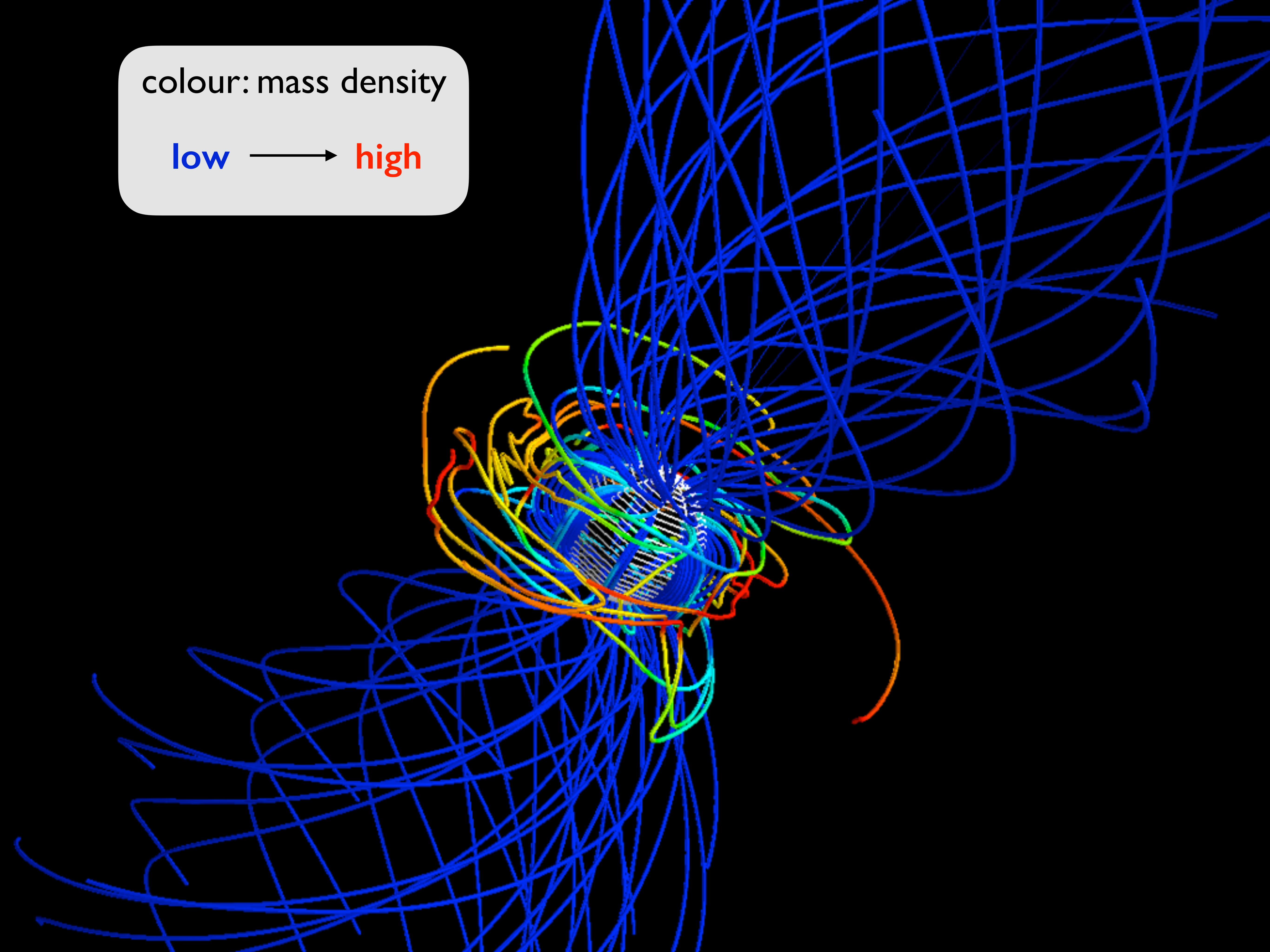
Romanova+ 2012


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

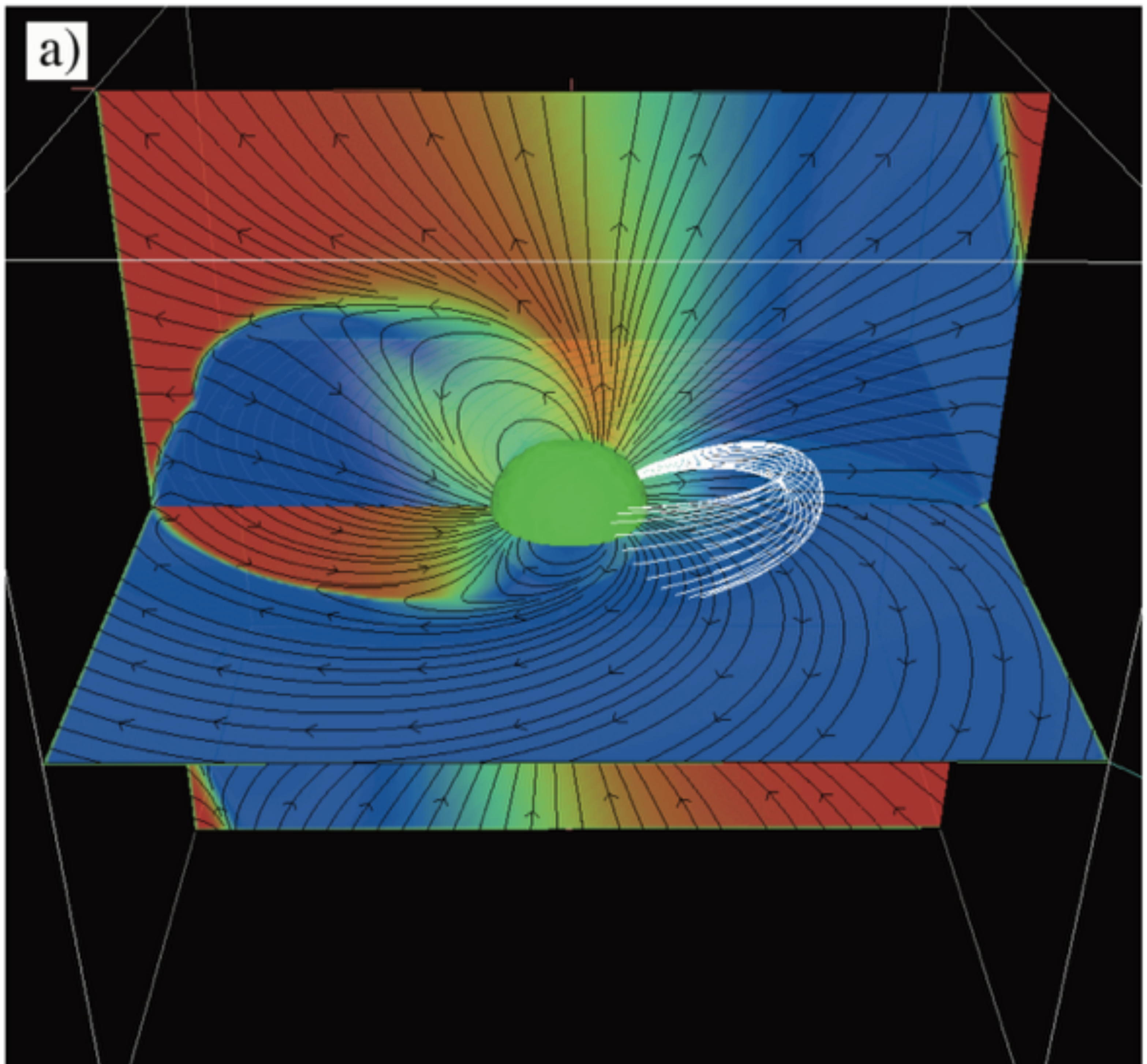
light cylinder: R_{LC} = 20




colour: mass density
low
high

Oblique rotators

Misaligned rotation and magnetic axes: true pulsars



isolated pulsar

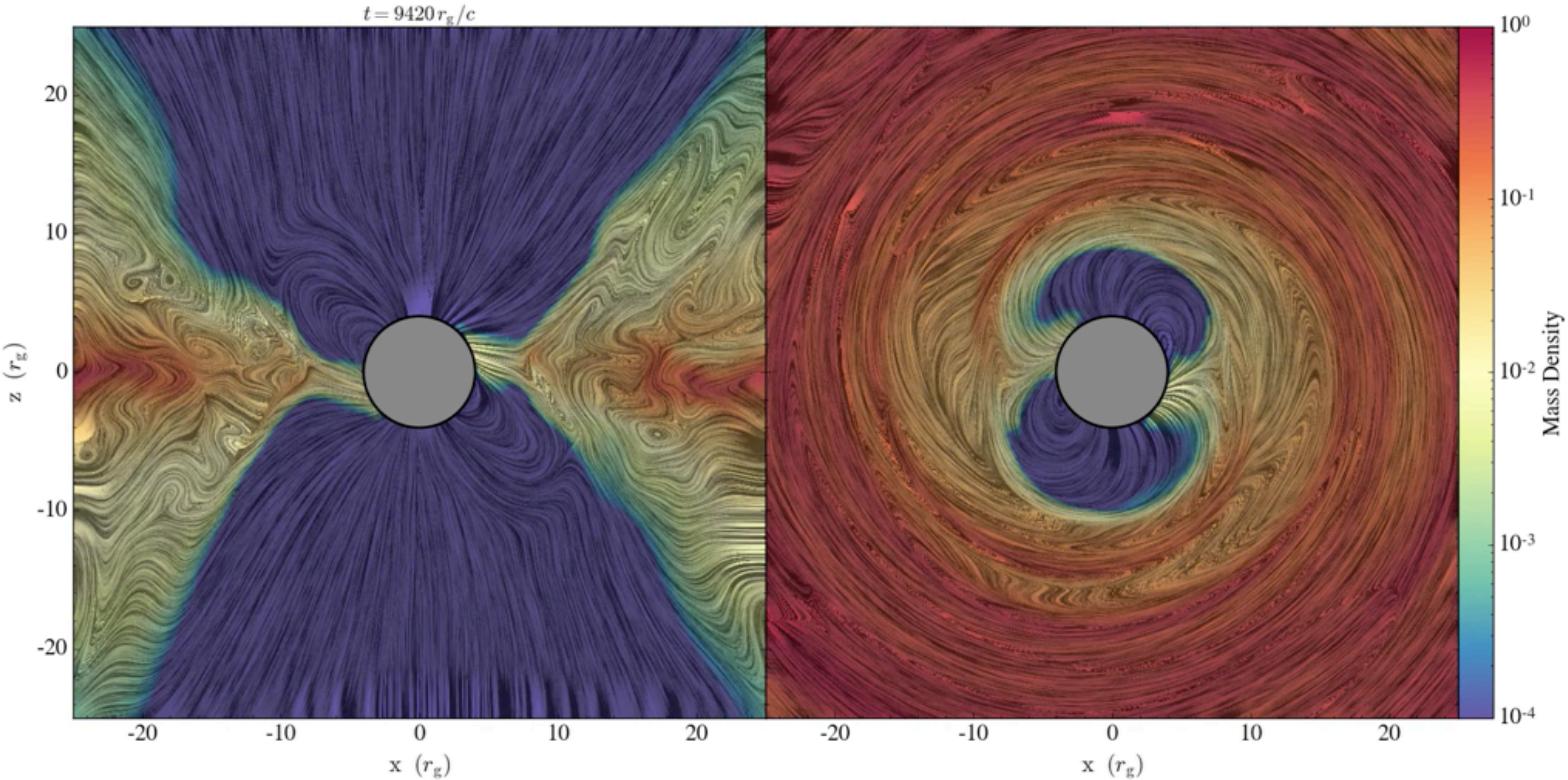
colour: toroidal B

χ = 60°

Spitkovsky 2006

stellar magnetic moment: μ = 10

χ = 45°



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 from millisecond pulsars

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