Electrodynamics of Accreting Millisecond Pulsars

ApJ 822, 33 / arXiv:1507.08627

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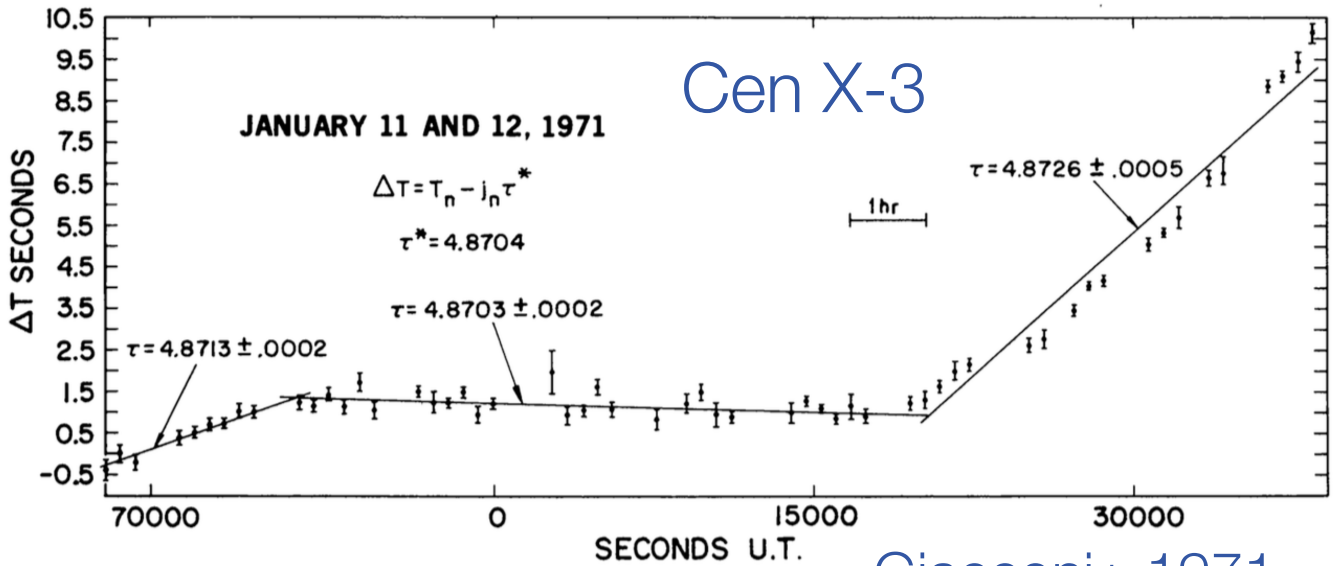
Observational puzzles

torques on accreting neutron stars

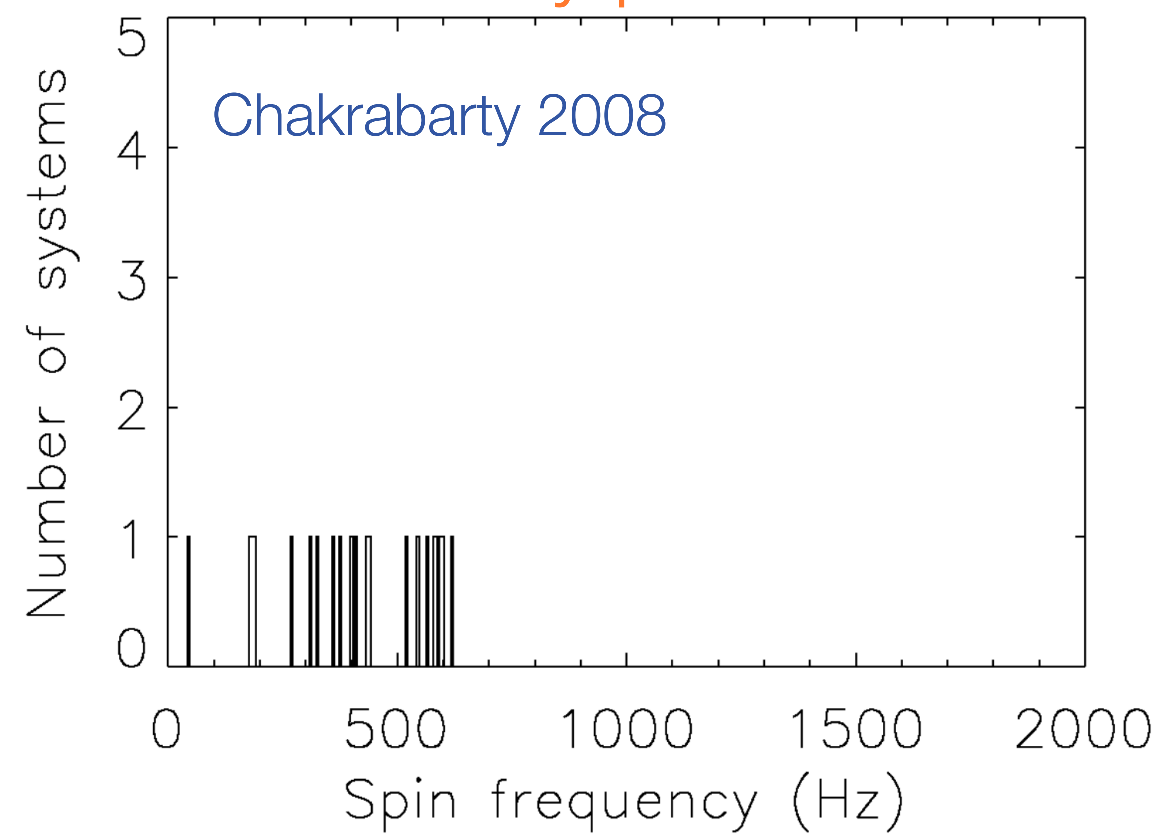
phase residuals

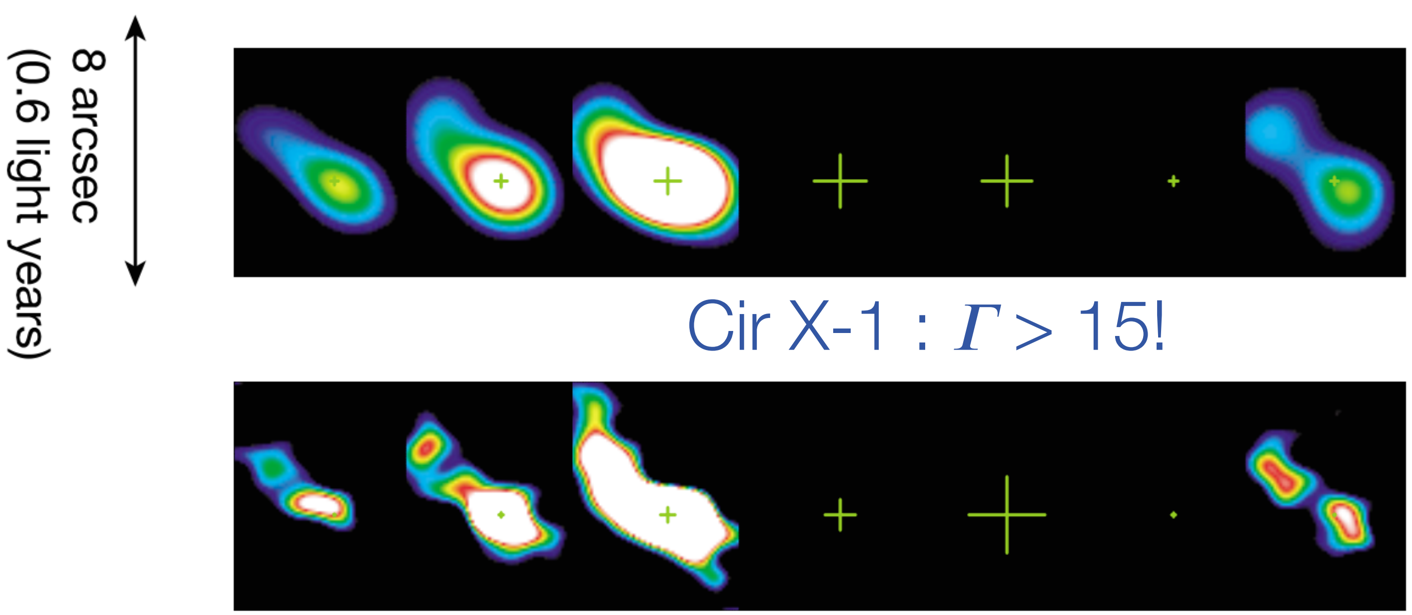
Cen X-3



Giacconi+ 1971

spin cutoff of millisecond X-ray pulsars





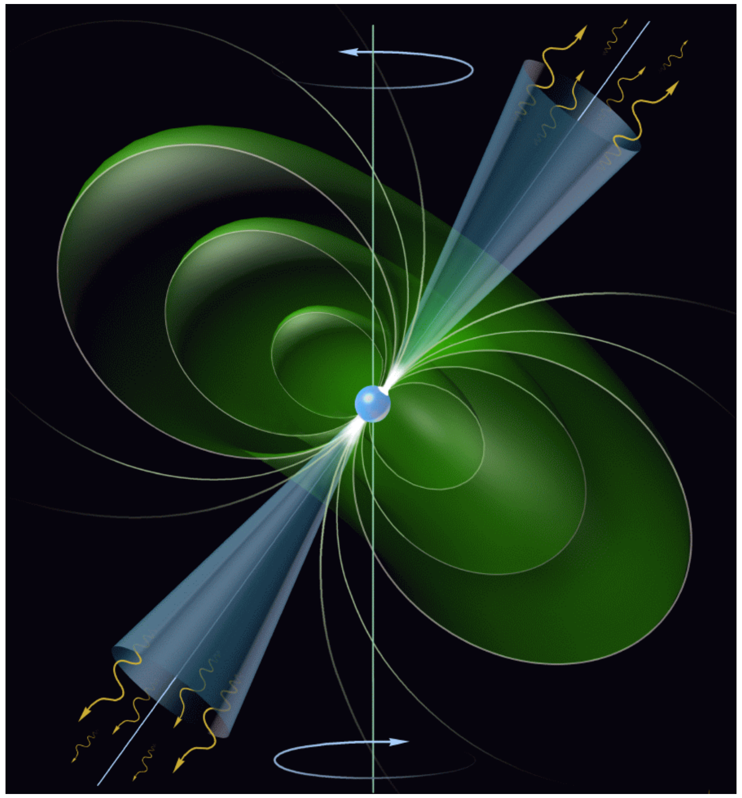
Cir X-1 : $\Gamma > 15$!

neutron star jets

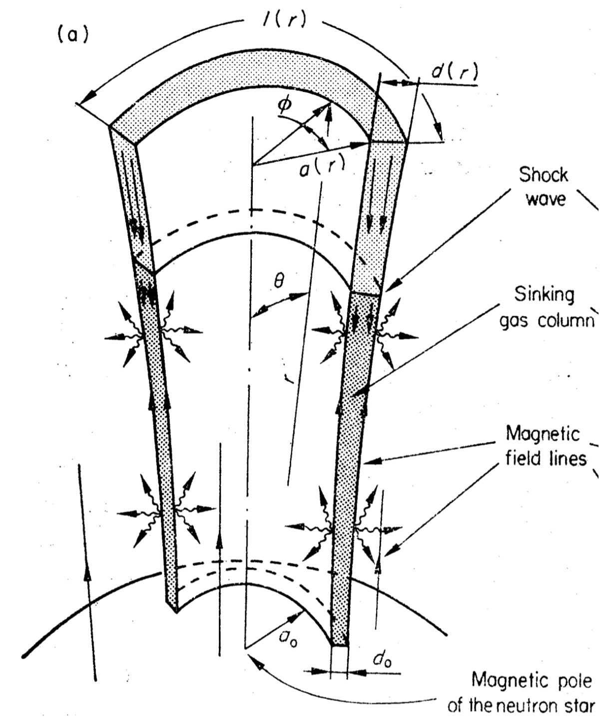
Fender+ 2004

Millisecond Pulsar Families

radio



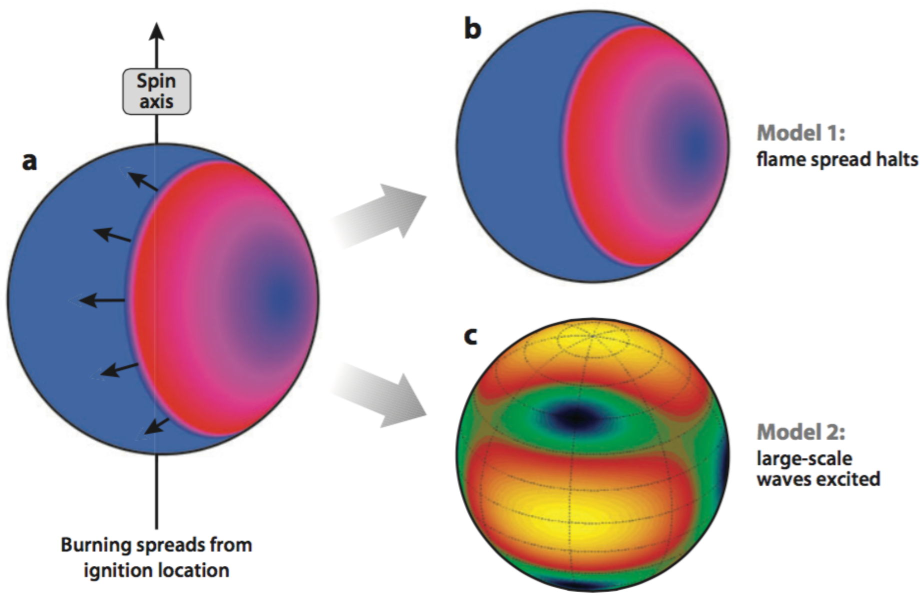
accretion-powered



X-rays from accretion column

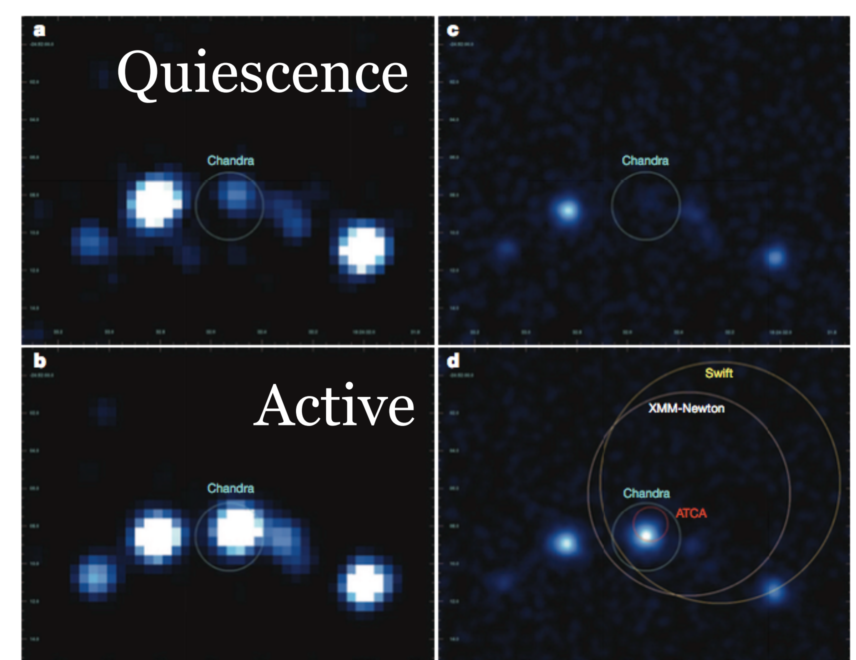
Basko & Sunyaev '76

nuclear-powered



Watts 2012

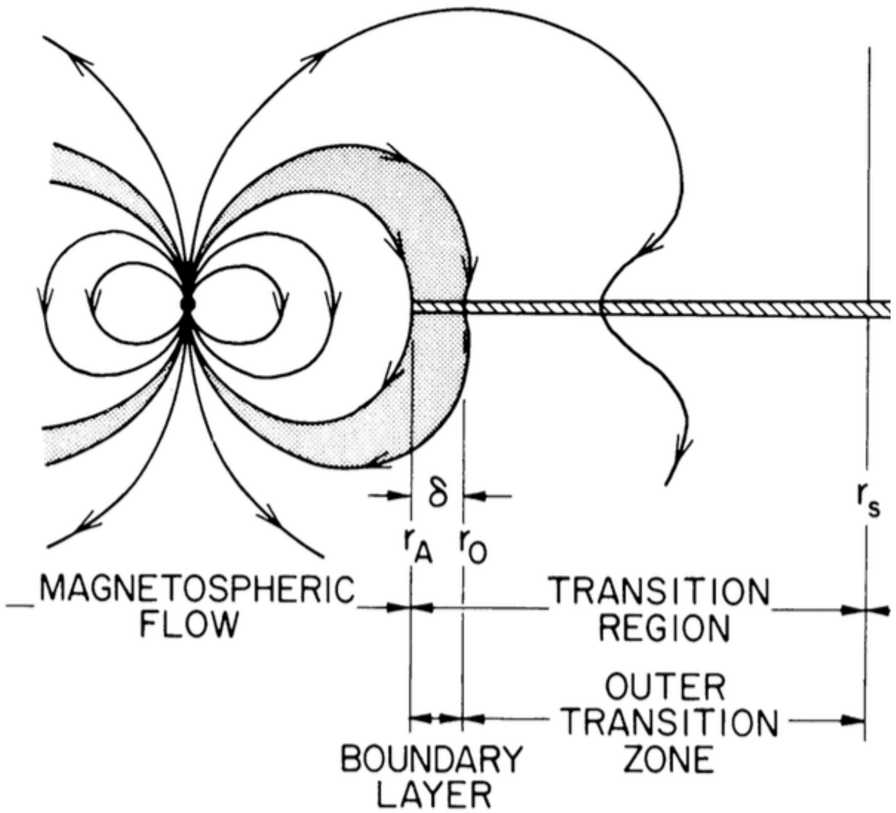
transitional



Papitto+ 2013

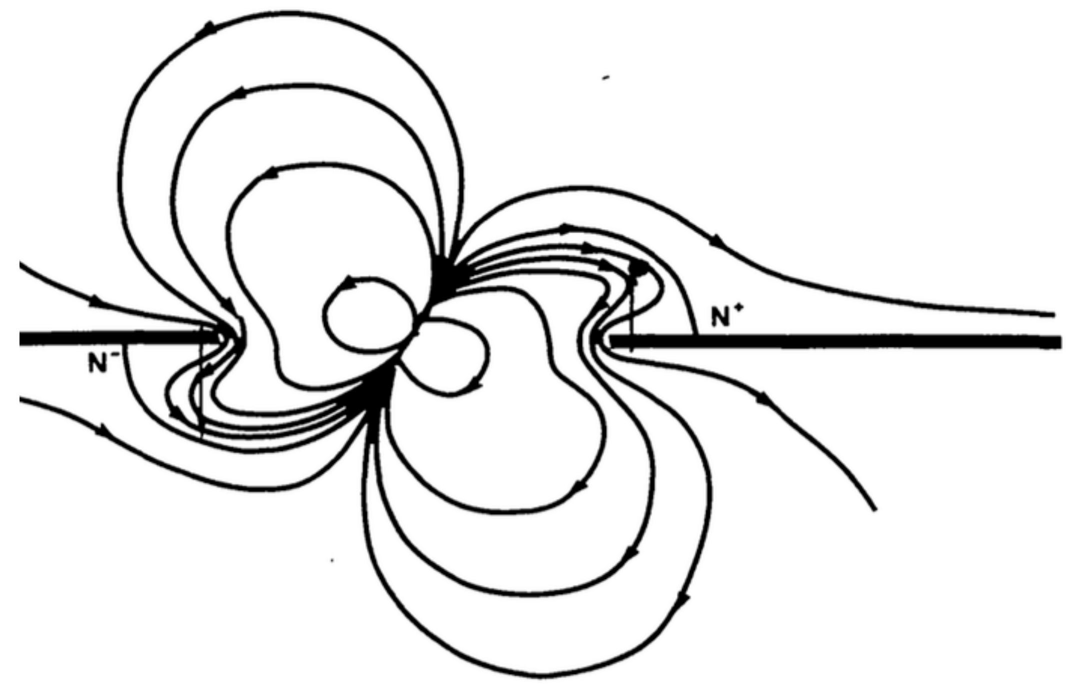
Global magnetospheric geometry

Closed…



Ghosh & Lamb 1978

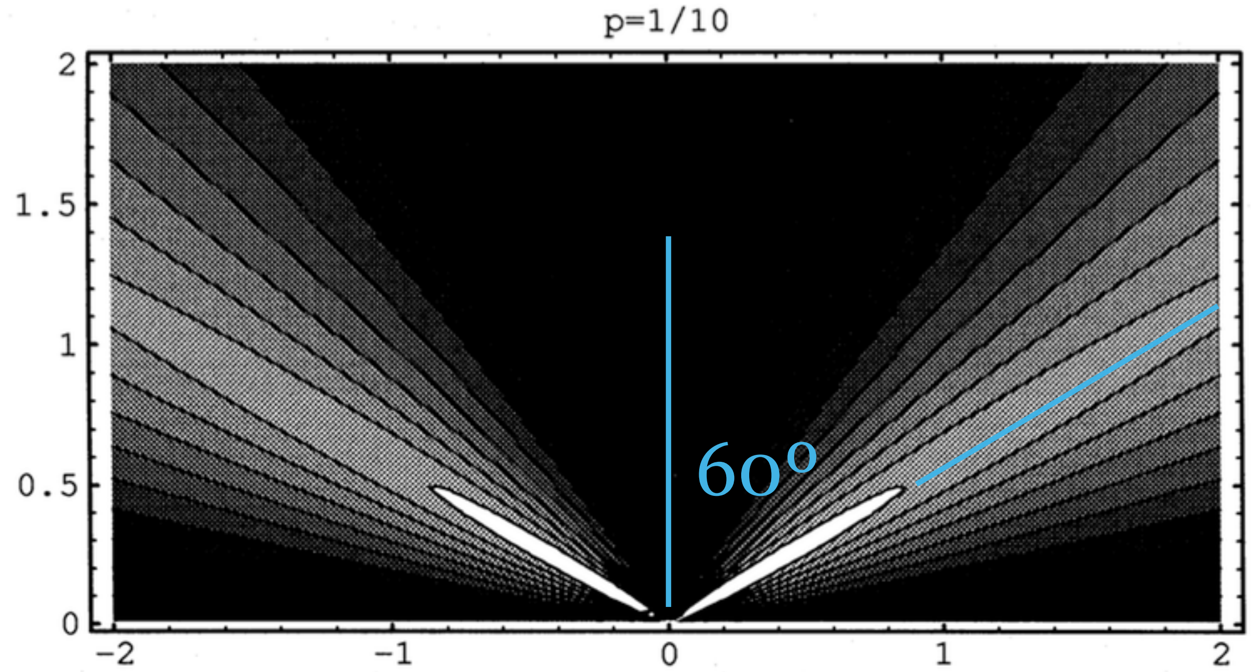
…or open?



Aly 1980

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

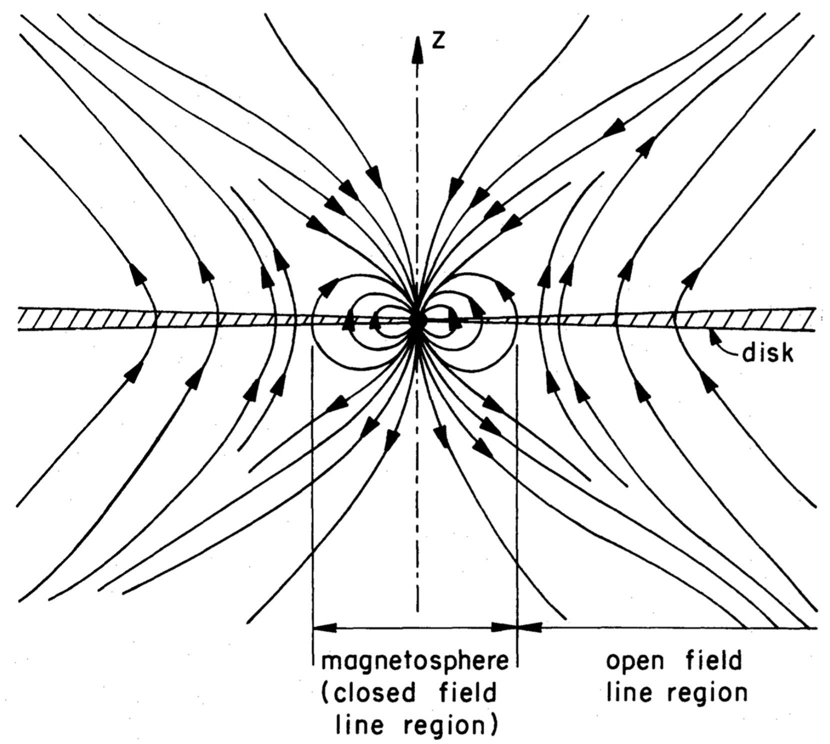
Field lines can be opened by disc



Twisting/winding causes field lines to open radially

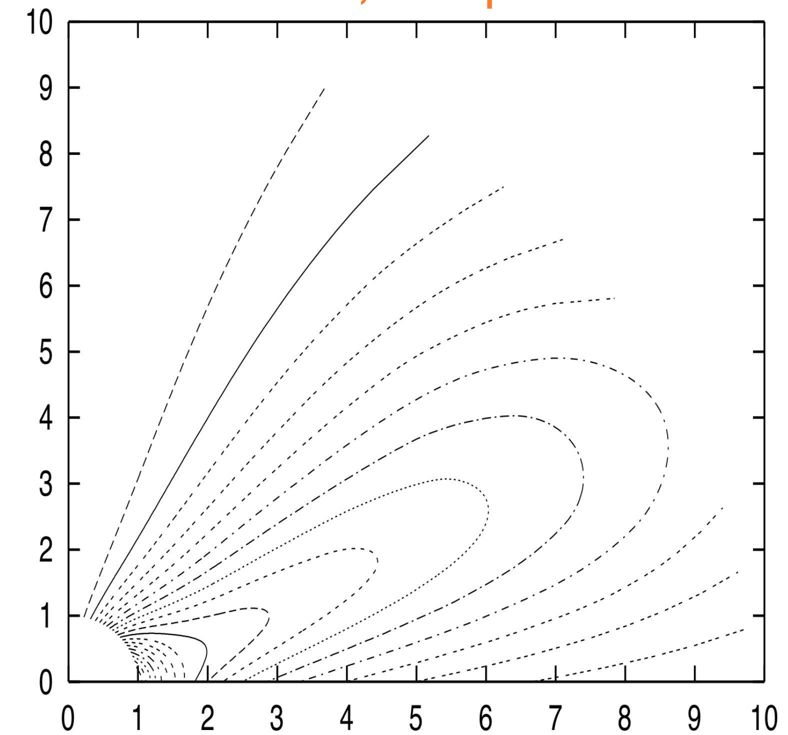
Lynden-Bell & Boily 1994

open field model for accreting star



Lovelace, Romanova, Bisnovatyi-Kogan 1995

steady-state solution at fixed twist; Keplerian disc

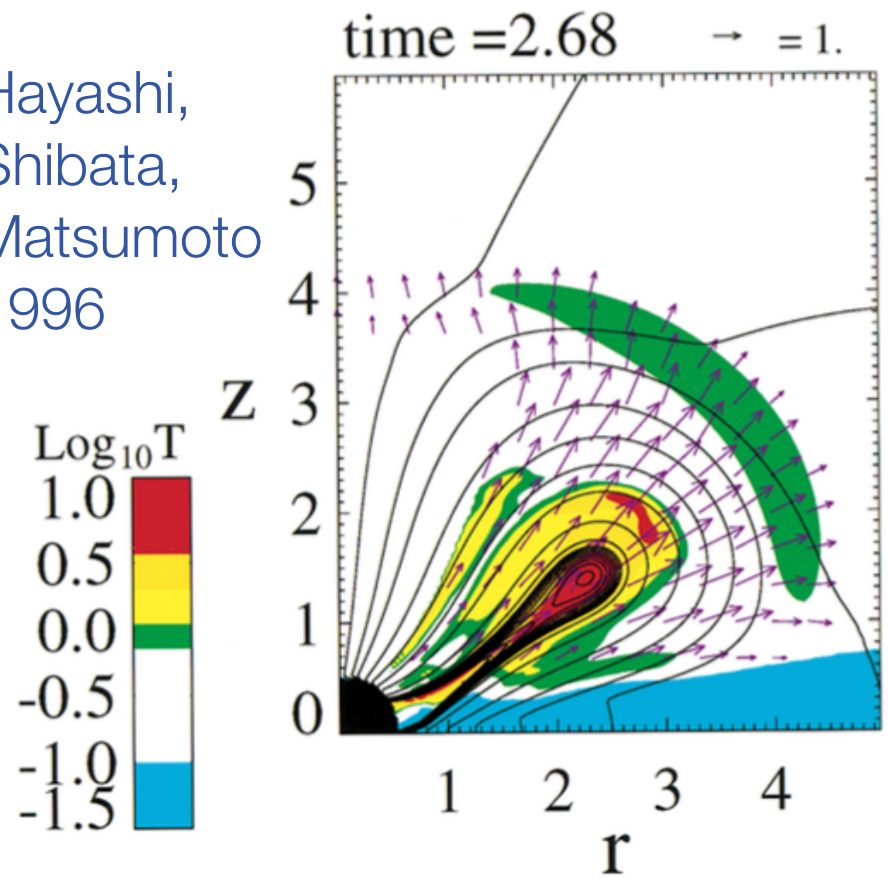


Uzdensky, Koenigl, Litwin 2002

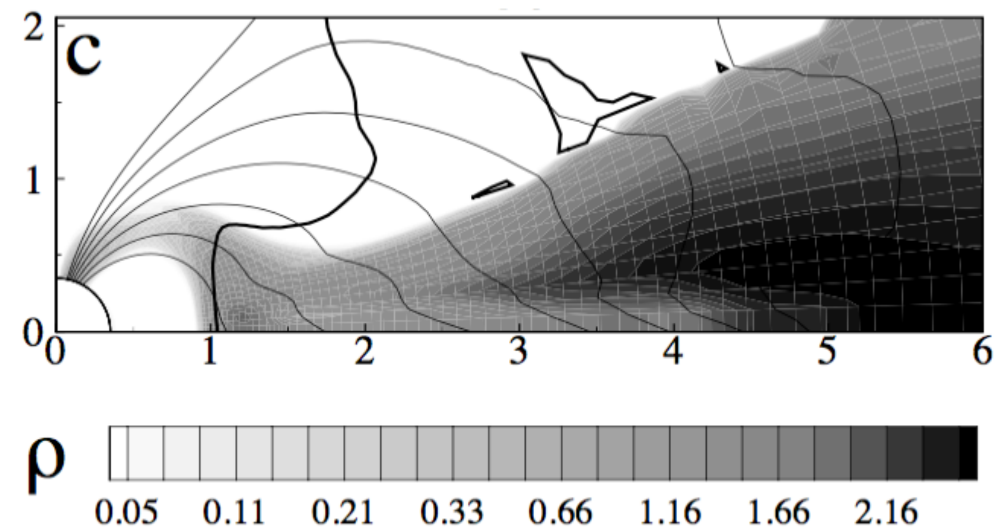
MHD simulations

opening + reconnection: flaring

Hayashi, Shibata, Matsumoto 1996

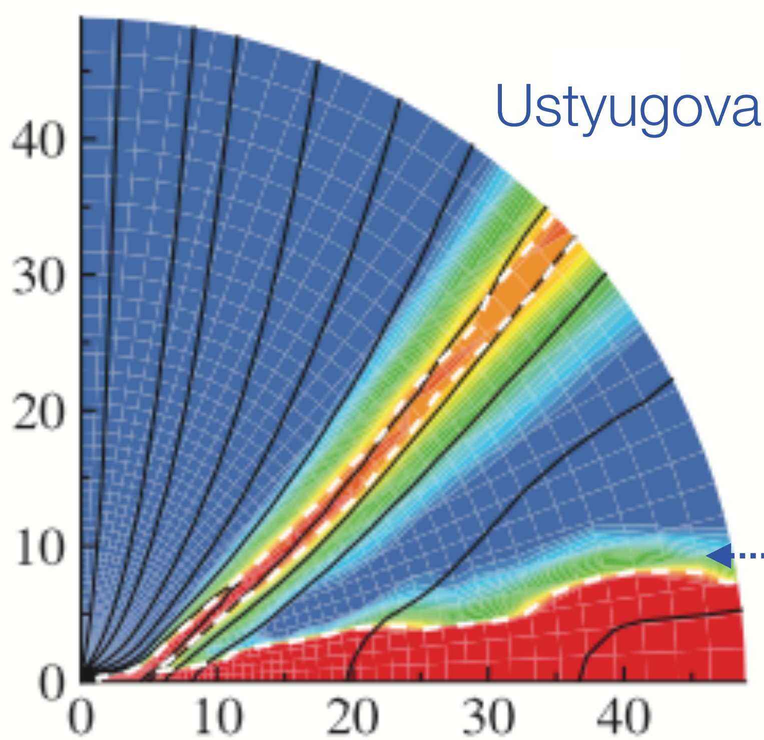


funnel flows & accretion torque



Romanova+ 2002

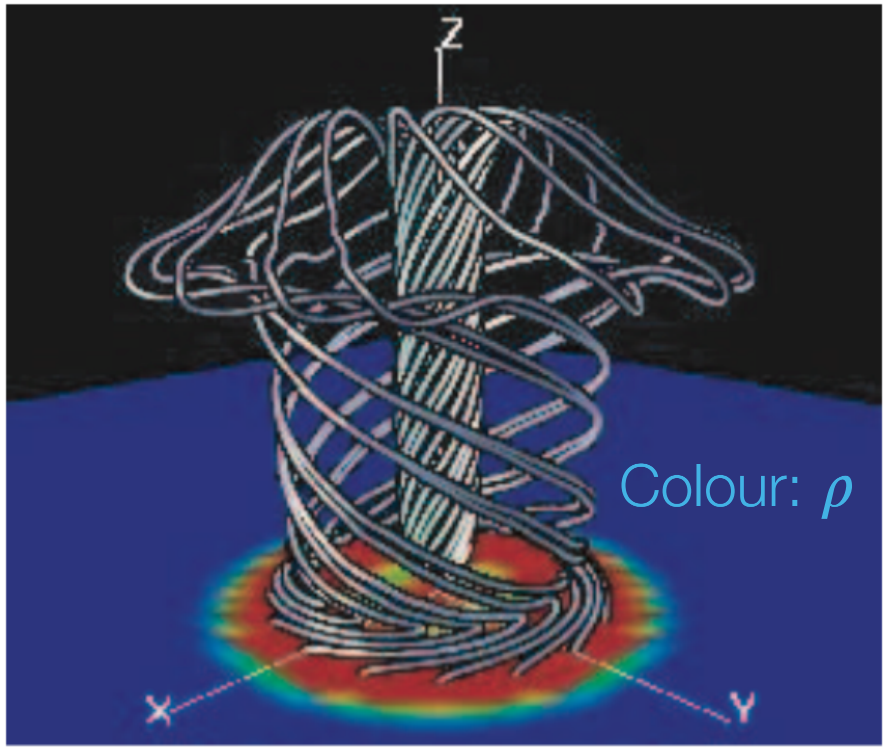
Ustyugova+ 2006



axial magnetised jet

$\beta = 1$ contour

Colour: plasma β



Colour: ρ

Kato, Hayashi, Matsumoto 2004

Millisecond pulsars: relativistic effects

1. All previous simulations were non-relativistic
2. Coronae/magnetospheres were heavy and fairly (numerically) diffusive

Explore relativistic regime with thinner discs

& lighter, nearly dissipationless coronae

↓

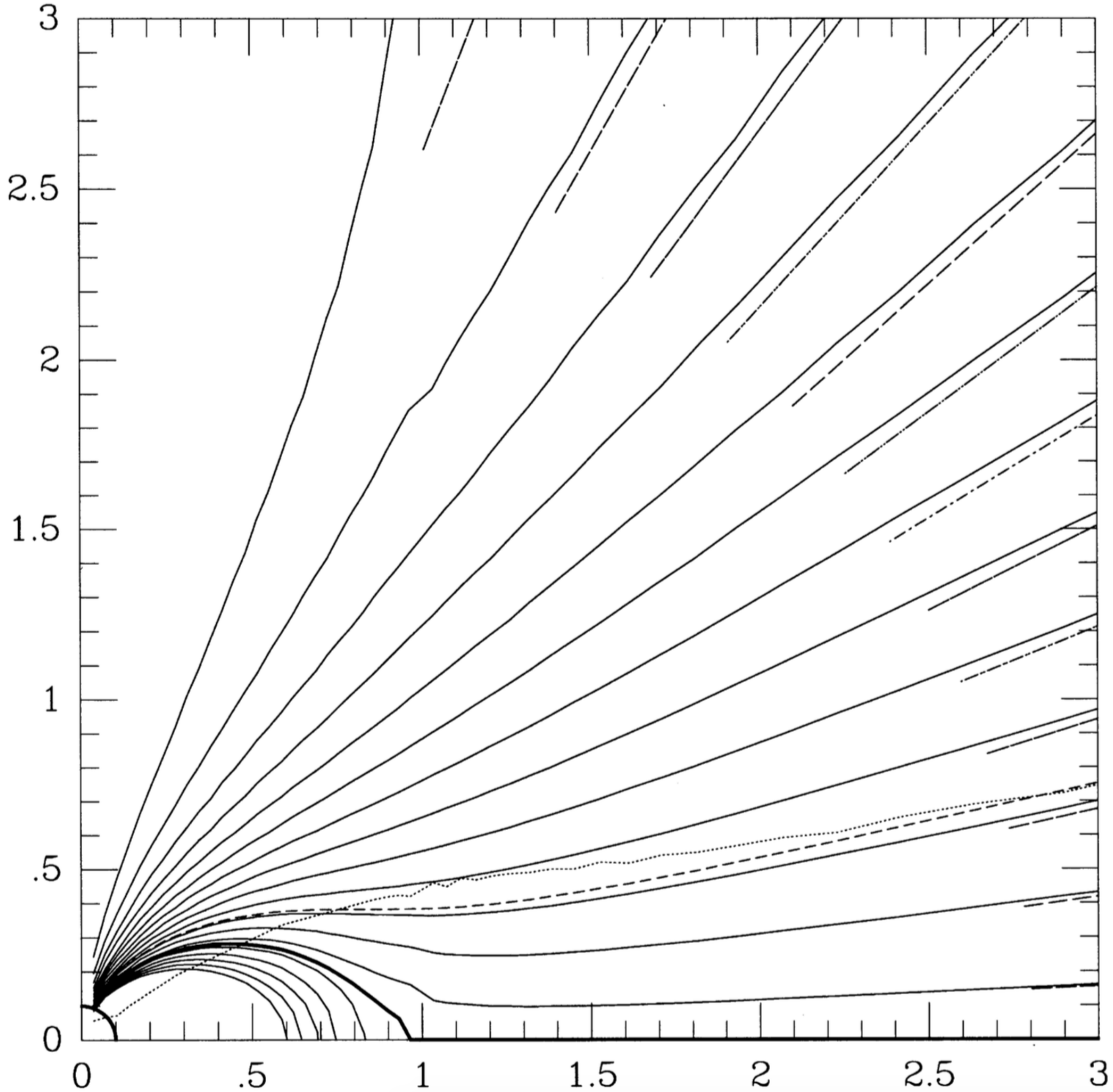
use broken force-free electrodynamics & PHAEDRA spectral code

KP, Beloborodov, Hui 2012

"broken": FFE + causal resistive corrections

KP 2016, in prep

Isolated Pulsars 101



Contopoulos, Kazanas, Fendt 99

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 05, Spitkovsky 06

Contopoulos 05

torque: $N = -L/\Omega$

Simulation set up

Solve Maxwell's equations with current $\boldsymbol{J}$

Dynamic Corona

Nearly ideal: $4\pi\sigma_0 = 2 \times 10^5\, c/r_*$

$$\boldsymbol{J} = \boldsymbol{J}_{\rm FFE} + \text{resistive corrections}$$

$$\frac{4\pi}{c}\boldsymbol{J} = \nabla\cdot\boldsymbol{E}\,\frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2+\tilde{E}^2} \quad + \left[\frac{\boldsymbol{B}\cdot\nabla\times\boldsymbol{B} - \boldsymbol{E}\cdot\nabla\times\boldsymbol{E} + \gamma\boldsymbol{E}\cdot\boldsymbol{B}}{1+\gamma\eta}\right]\frac{\boldsymbol{B}}{B^2}$$

implemented via dynamic resistivity: $\eta = \eta_0 + \eta_1\left|\frac{\boldsymbol{J}_{\rm FFE}\cdot\boldsymbol{B}}{B^2+E^2}\right|$

Kinematic Disc

α-disc model: $\alpha_{\rm SS} = 0.1 \qquad {\rm Pr_m} = 1$

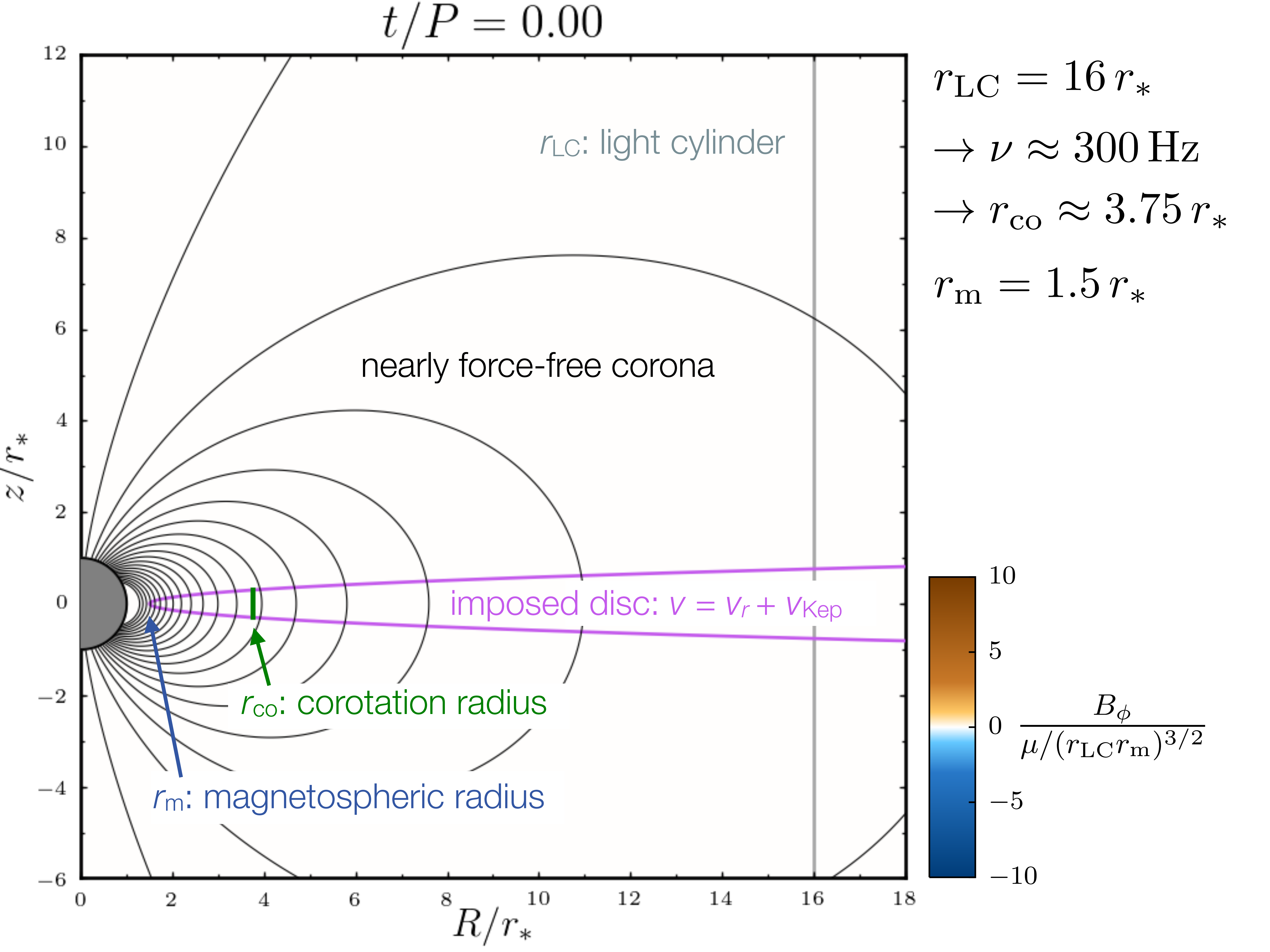
$$v_{\hat{r}} = \alpha_{\rm SS}\left(\frac{h}{r}\right)^2 v_{\rm Kepler}$$

$$v_{\hat{\phi}} = v_{\rm Kepler}$$

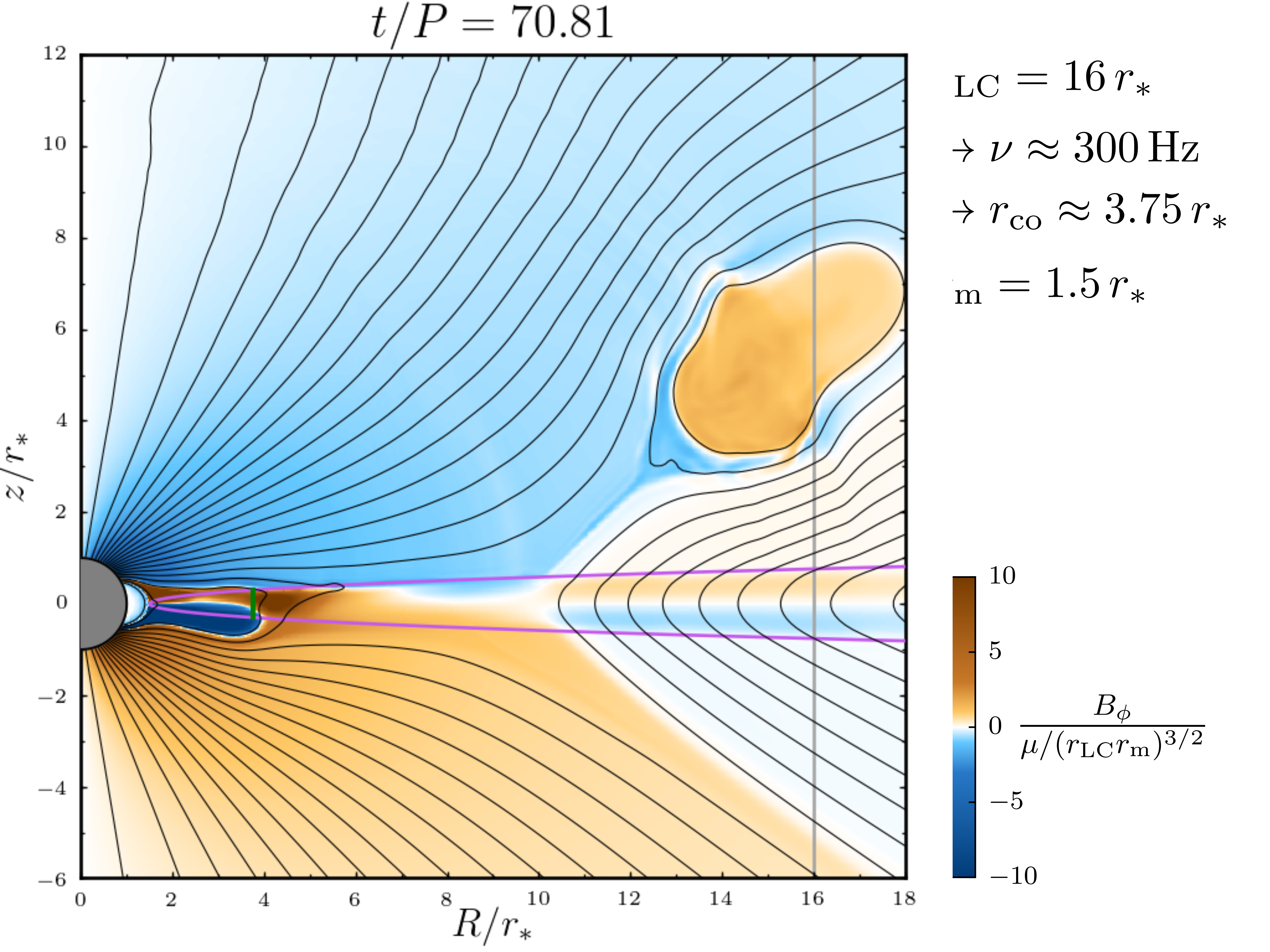
$$4\pi\sigma = \left[\alpha_{\rm SS}(h^2/r)v_{\rm Kepler}\right]^{-1}{\rm Pr_m}\,c^2$$

$$\sim 2\times 10^3\,c/r_*$$

$$\boldsymbol{J} = \Gamma\sigma\left[\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B}/c - (\boldsymbol{v}\cdot\boldsymbol{E})\boldsymbol{v}/c^2\right] + \rho_{\rm e}\boldsymbol{v}$$

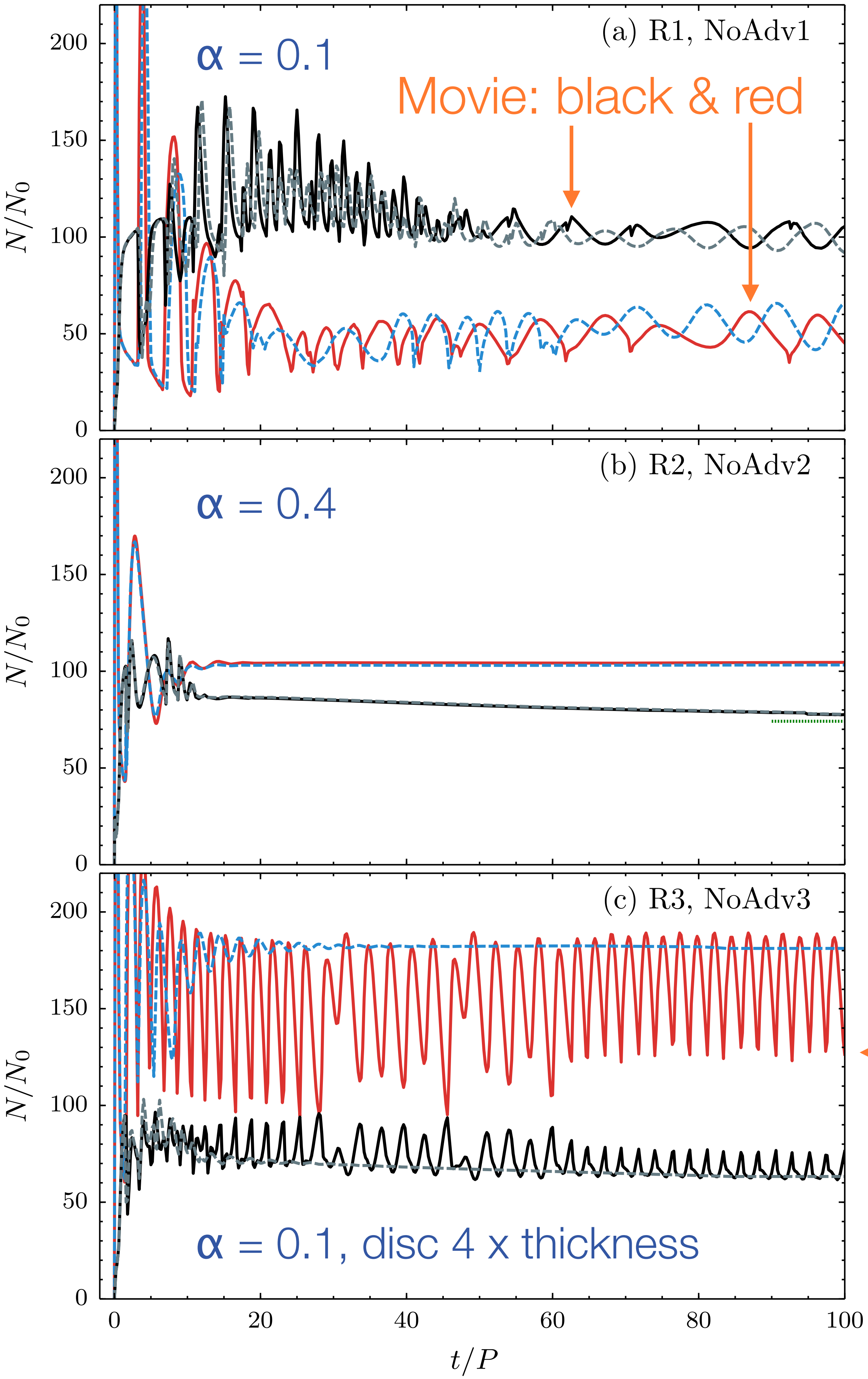


$t/P = 0.00$
r_{LC}: light cylinder
nearly force-free corona
imposed disc: $v = v_r + v_{Kep}$
r_{co}: corotation radius
r_m: magnetospheric radius
z/r_*
R/r_*
12
10
8
6
4
2
0
−2
−4
−6
0
2
4
6
8
10
12
14
16
18
$r_{LC} = 16\, r_*$
$\rightarrow \nu \approx 300\,\mathrm{Hz}$
$\rightarrow r_{co} \approx 3.75\, r_*$
$r_m = 1.5\, r_*$
10
5
0
−5
−10
$\frac{B_\phi}{\mu/(r_{LC} r_m)^{3/2}}$

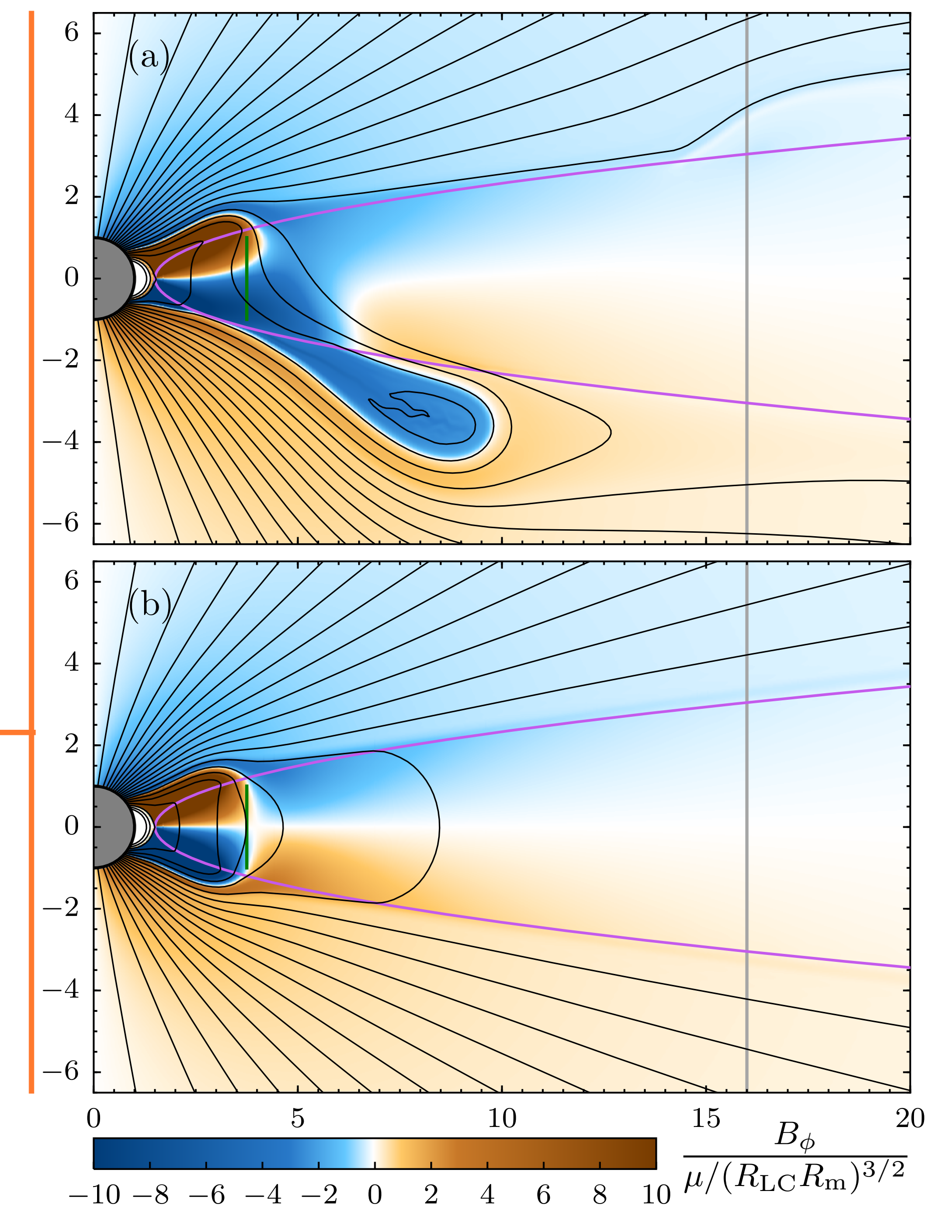


$t/P = 70.81$
z/r_*
R/r_*
$_{\mathrm{LC}} = 16\, r_*$
$\rightarrow \nu \approx 300\,\mathrm{Hz}$
$\rightarrow r_{\mathrm{co}} \approx 3.75\, r_*$
$_{\mathrm{m}} = 1.5\, r_*$
$\frac{B_\phi}{\mu/(r_{\mathrm{LC}} r_{\mathrm{m}})^{3/2}}$

Torques on the pulsar



Spin-up, $v_r \neq 0$
Spin-up, $v_r = 0$
Spin-down, $v_r \neq 0$
Spin-down, $v_r = 0$



Full disc model

solid lines (black & red)

No v_r in disc

dashed lines (grey & blue)

Field lines: dragged in or "pushed" out?

Get nearly the same final steady state when disc has $v_r = 0$

	$N_{\rm spindown}/N_0$
v_r from α-disc model	74.2
$v_r = 0$	74.5

← N_0: torque on equivalent isolated pulsar

Estimate outward field line speed

→ resistive annihilation of the radial field: $v_{\rm resist} \approx \dfrac{\nu_{\rm m}}{h} \tan\theta_{\rm B}$

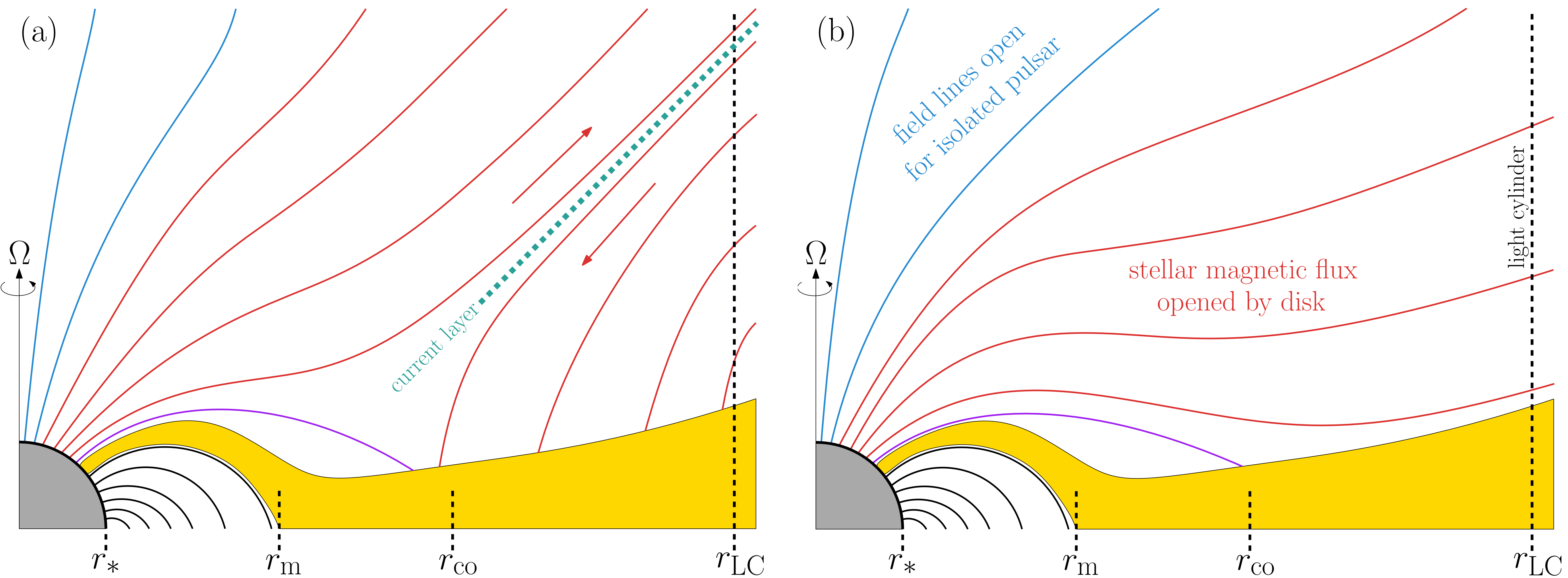
angle at which field lines enter disc

therefore $$\frac{v_{\rm accrete}}{v_{\rm resist}} \approx \frac{h}{r} \frac{{\rm Pr_m}}{\tan\theta_{\rm B}}$$

So for thin discs can ~ neglect disc accretion velocity

Taking stock — a toy model

Approximate all spin-down torque
as coming from open field lines



KP, Spitkovsky, Beloborodov 2016

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

Simple model for torques

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

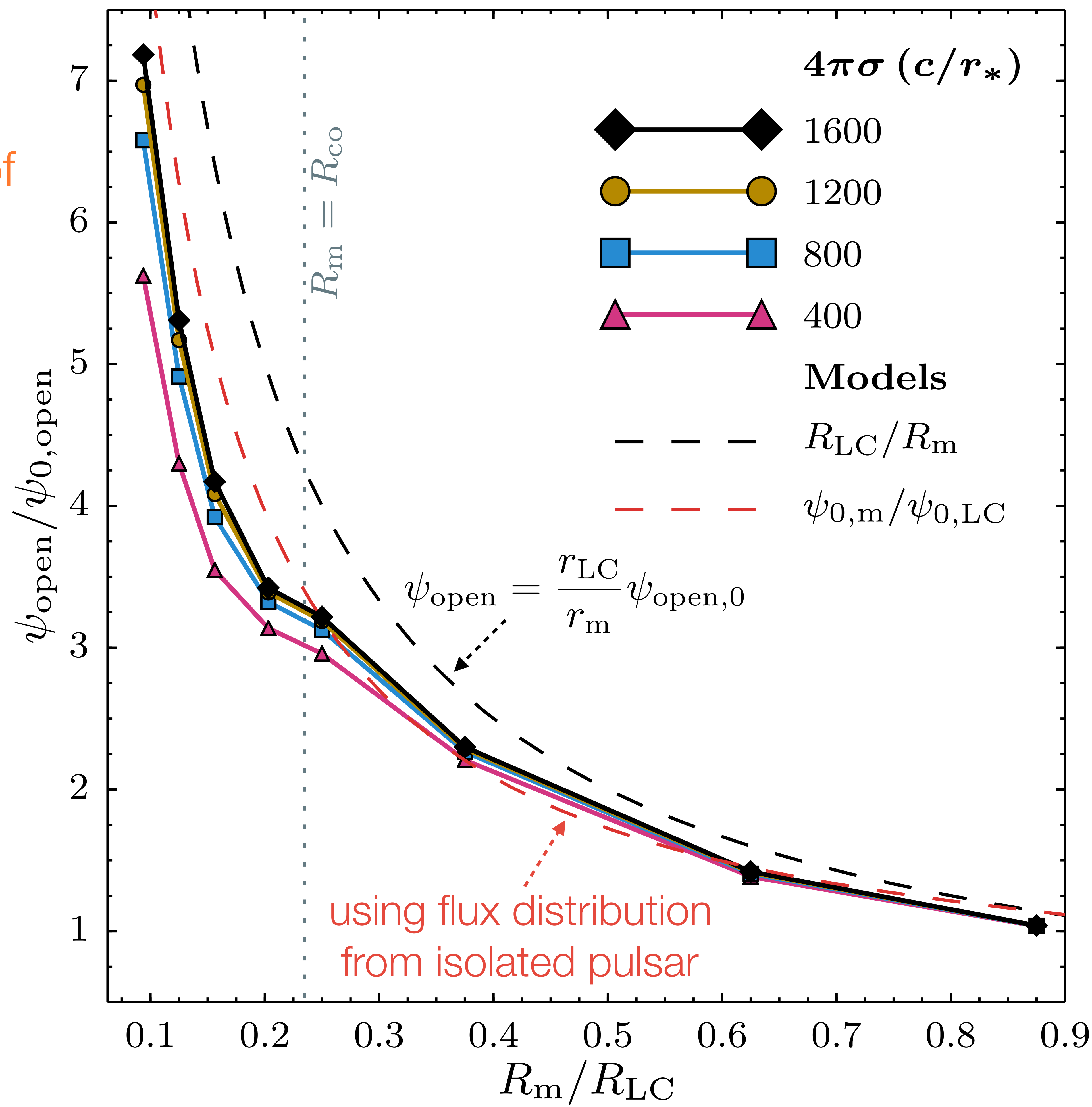
Torque: $$N_{\mathrm{down,open}} = \zeta^2\left(\frac{r_{\mathrm{LC}}}{r_{\mathrm{m}}}\right)^2 N_0$$

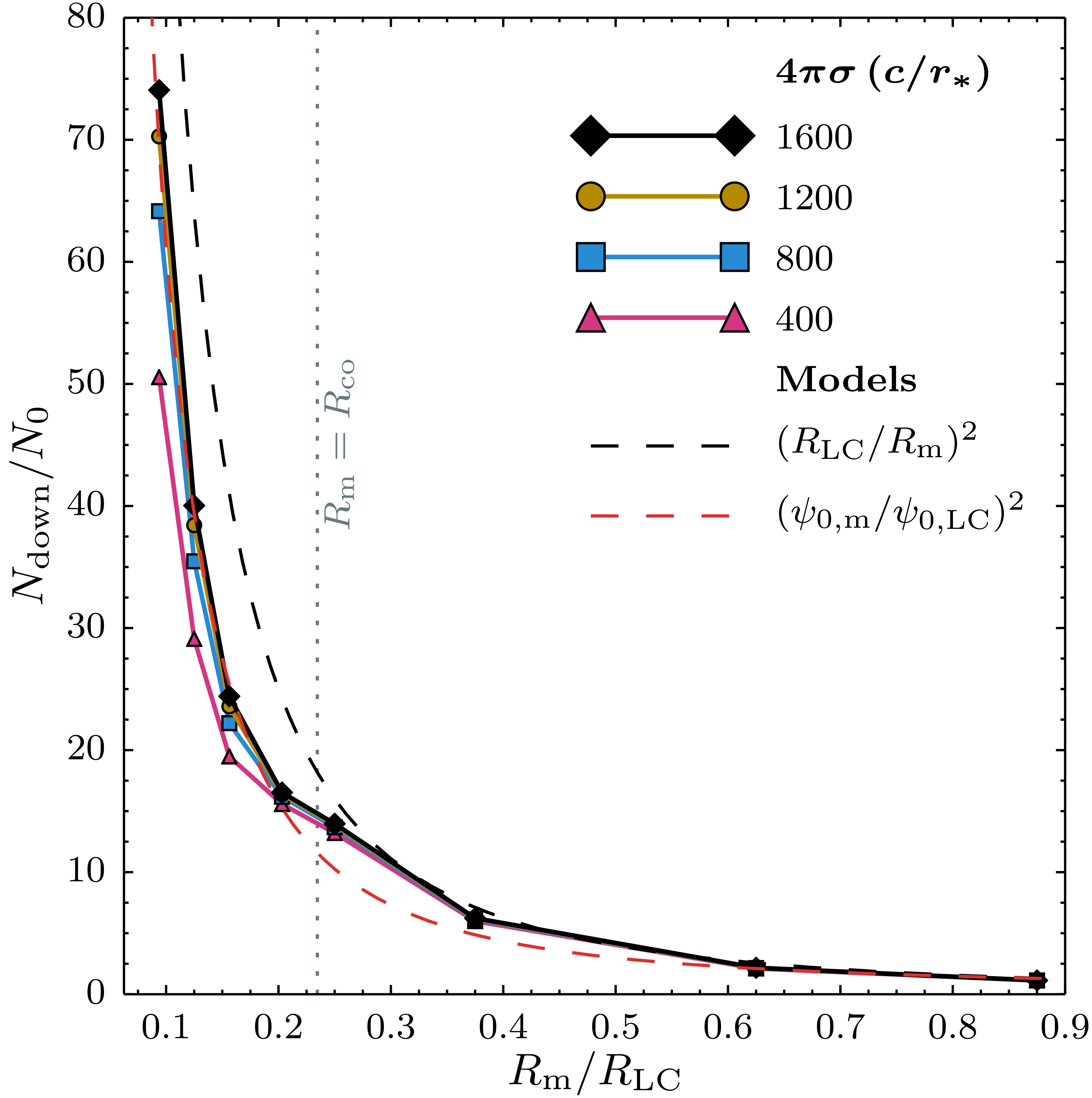
$$N_{\mathrm{tot}} = \begin{cases} \dot{M}\sqrt{GMr_{\mathrm{m}}} - \zeta^2\frac{\mu^2}{r_{\mathrm{m}}^2}\frac{\Omega}{c}, & r_{\mathrm{m}} < r_{\mathrm{co}} \\ -\zeta^2\frac{\mu^2}{r_{\mathrm{m}}^2}\frac{\Omega}{c}, & r_{\mathrm{co}} < r_{\mathrm{m}} < r_{\mathrm{LC}} \\ -\mu^2\frac{\Omega^3}{c^3}, & r_{\mathrm{m}} > r_{\mathrm{LC}}. \end{cases}$$

Simulations: grid of simplified models

$v_r = 0$

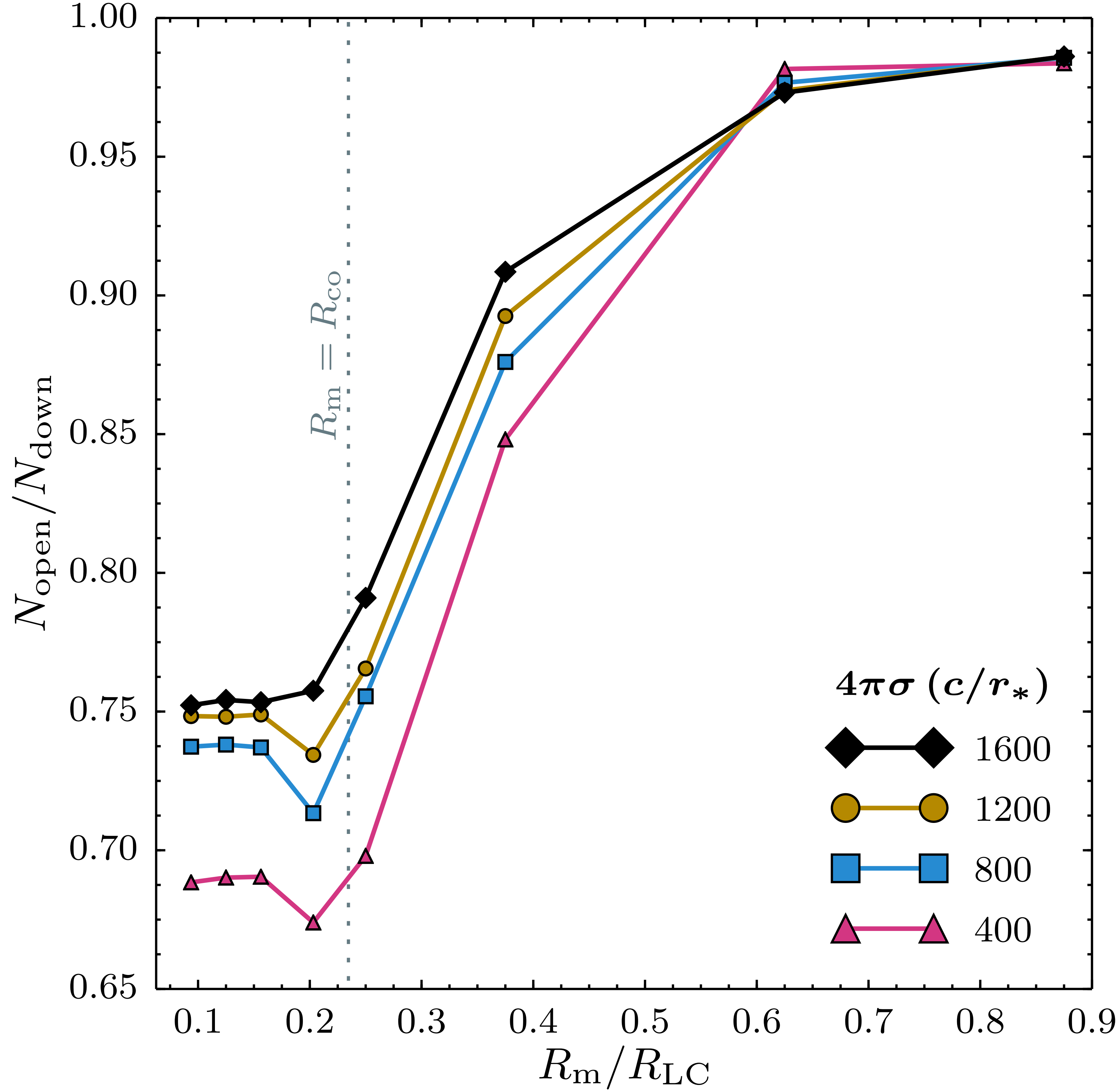
$\sigma = \text{const}$

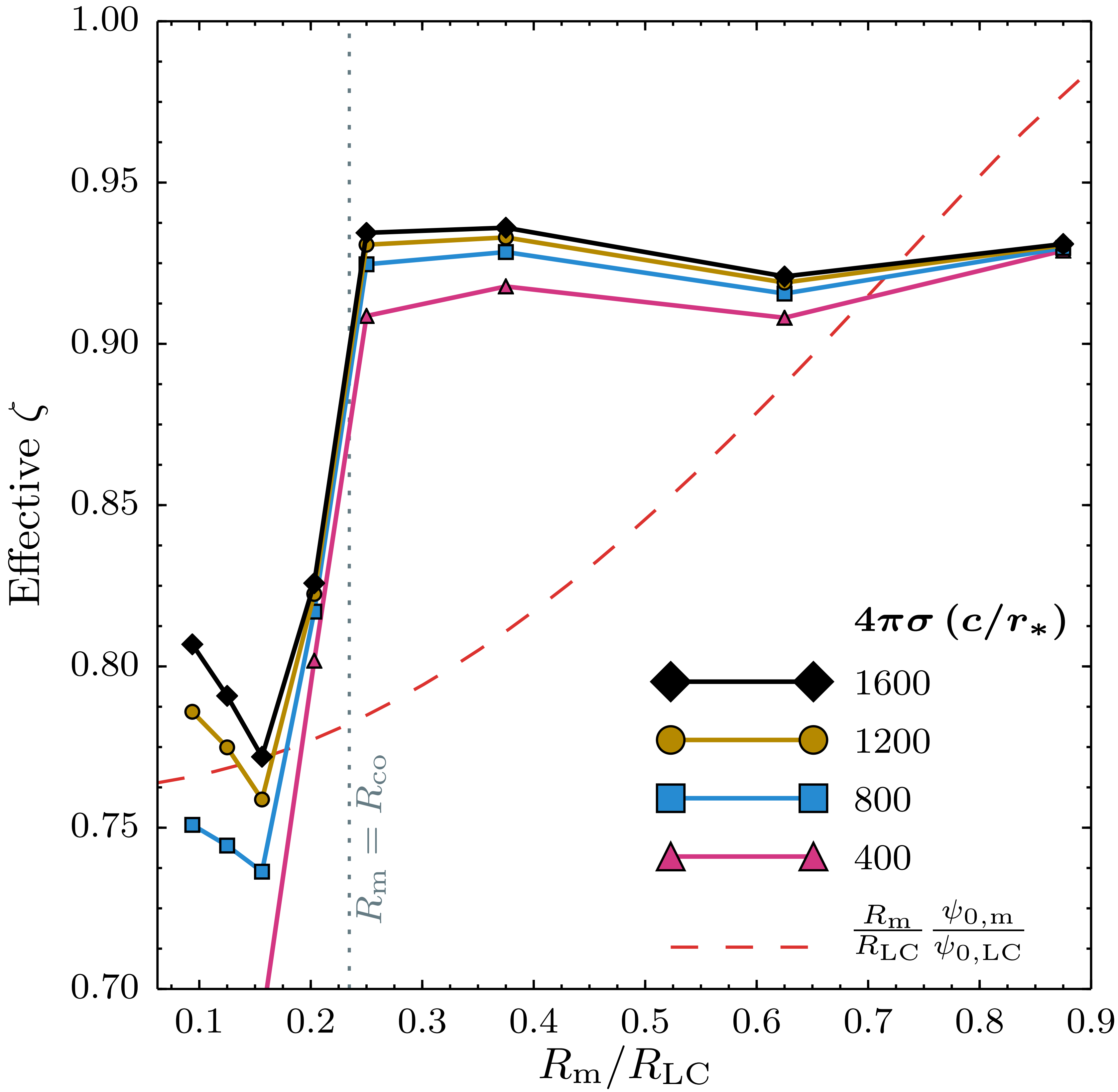




total spin-down torque
vs
magnetospheric
radius

fraction of spin-down torque applied by open field lines





Effective flux-opening efficiency

Found using

$$\zeta = \left(\frac{R_{mag}}{R_{LC}}\right)\sqrt{\frac{N_{down}}{N_0}}$$

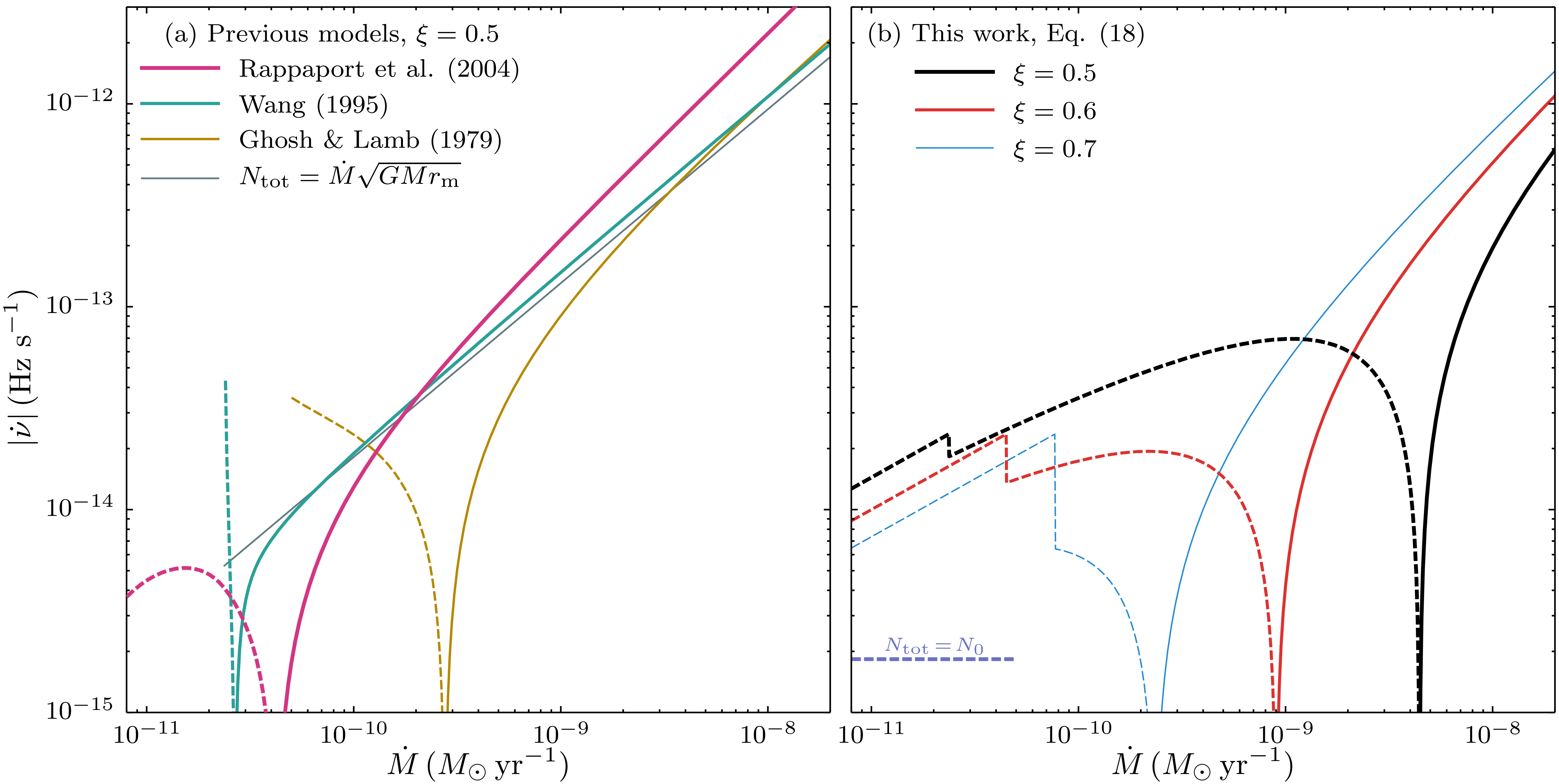
where N_{down} is the *total* spin-down torque*

↓

model provides good estimate for comparing to observations

* for open-flux torque, multiply by $(N_{open}/N_{down})^{1/2}$

Torque models: 500 Hz, 10^8 G star



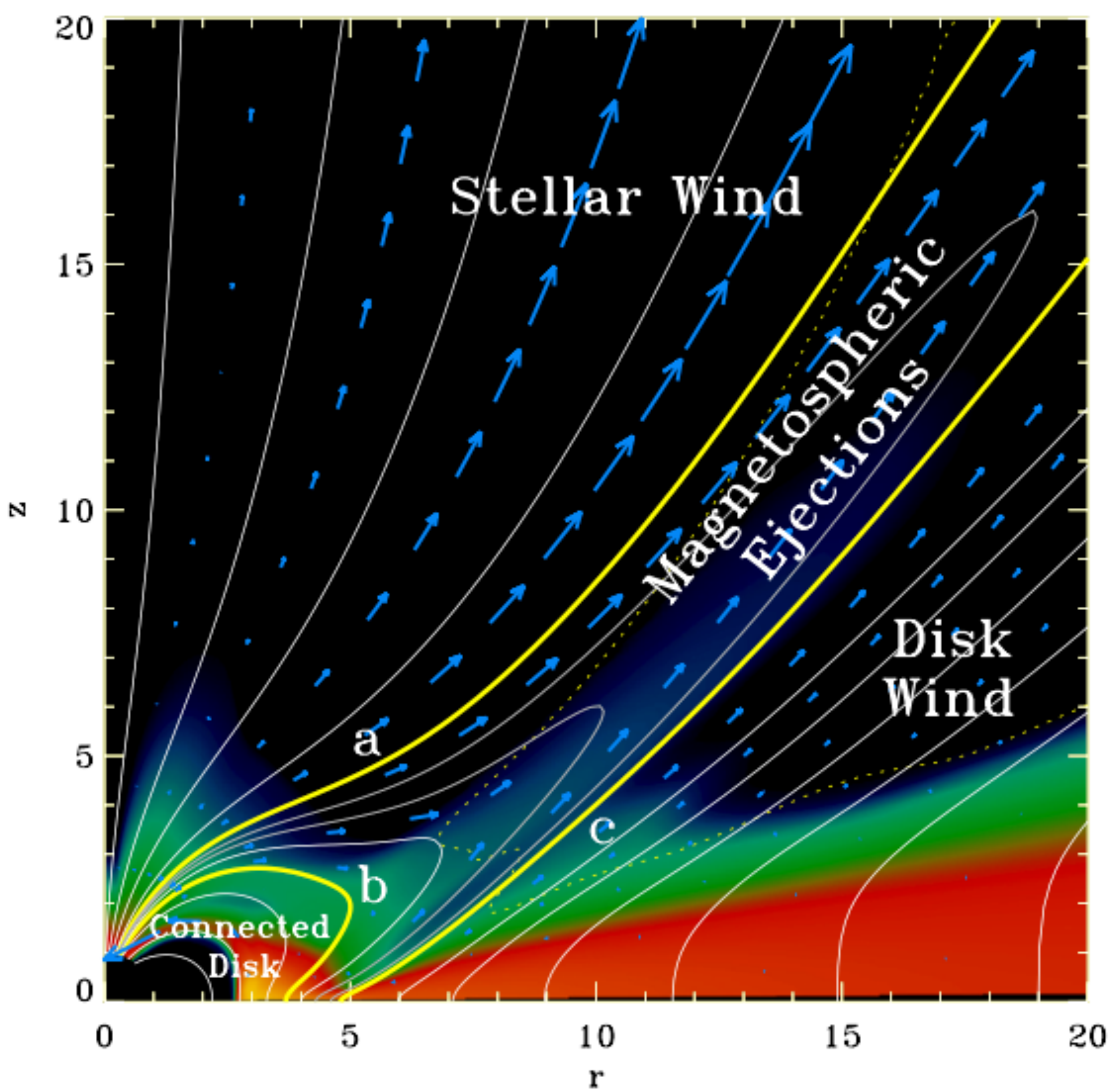
KP, Spitkovsky, Beloborodov 2016

relating $r_{\rm m} = \xi r_{\rm A}$ where Alfvén radius $r_{\rm A} = \left(\frac{\mu^4}{2GM\dot{M}^2}\right)^{1/7}$

Jet power — if open flux is collimated

Scale with open flux in same way: $L_\mathrm{j} = \zeta^2 \left(\frac{r_\mathrm{LC}}{r_\mathrm{m}}\right)^2 L_0$

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



Zanni & Ferreira 2013

colour: mass density

Application 1: Torques on AMSPs

Test torque models when get a magnetic moment estimate via spin measurements during multiple outbursts

For reasonable parameters, can explain lack of detectable spin-up during outbursts of

Haskell & Patruno 2011

SAX J1808.4-3658

$$\xi < [0.65,\ 0.61,\ 0.55]$$
$$\text{for } \zeta = [1.0,\ 0.9,\ 0.8]$$

XTE J1814-338*

* assuming B ~ 10^8 G

$$\xi < [0.72,\ 0.67,\ 0.61,\ 0.56]$$
$$\text{for } \zeta = [1.0,\ 0.9,\ 0.8,\ 0.7]$$

No enhanced/anomalous spin-down needed for

XTE J1751-305 — Papitto+ 2008, Riggio+ 2011

IGR J00291+5934 — Patruno 2010, Hartman+ 2011, Papitto+ 2011

Application 2: Spin equilibrium

Spin-up from $r_{\rm m}$ = Spin-down on open flux

$$\dot{M}\sqrt{GMr_{\rm m}} = -\zeta^2 \left(\frac{r_{\rm LC}}{r_{\rm m}}\right)^2 N_0$$

↓

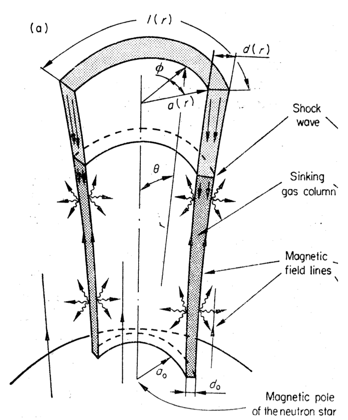
$$\nu_{\rm eqlm} = 956\,\zeta^{-2}\xi^{5/2}\left(\frac{\mu}{10^{26}\ {\rm G\,cm^3}}\right)^{-4/7} \times \left(\frac{M}{1.4\,M_\odot}\right)^{1/7}\left(\frac{\dot{M}}{10^{-10}\ M_\odot\,{\rm yr}^{-1}}\right)^{2/7}\ {\rm Hz}$$

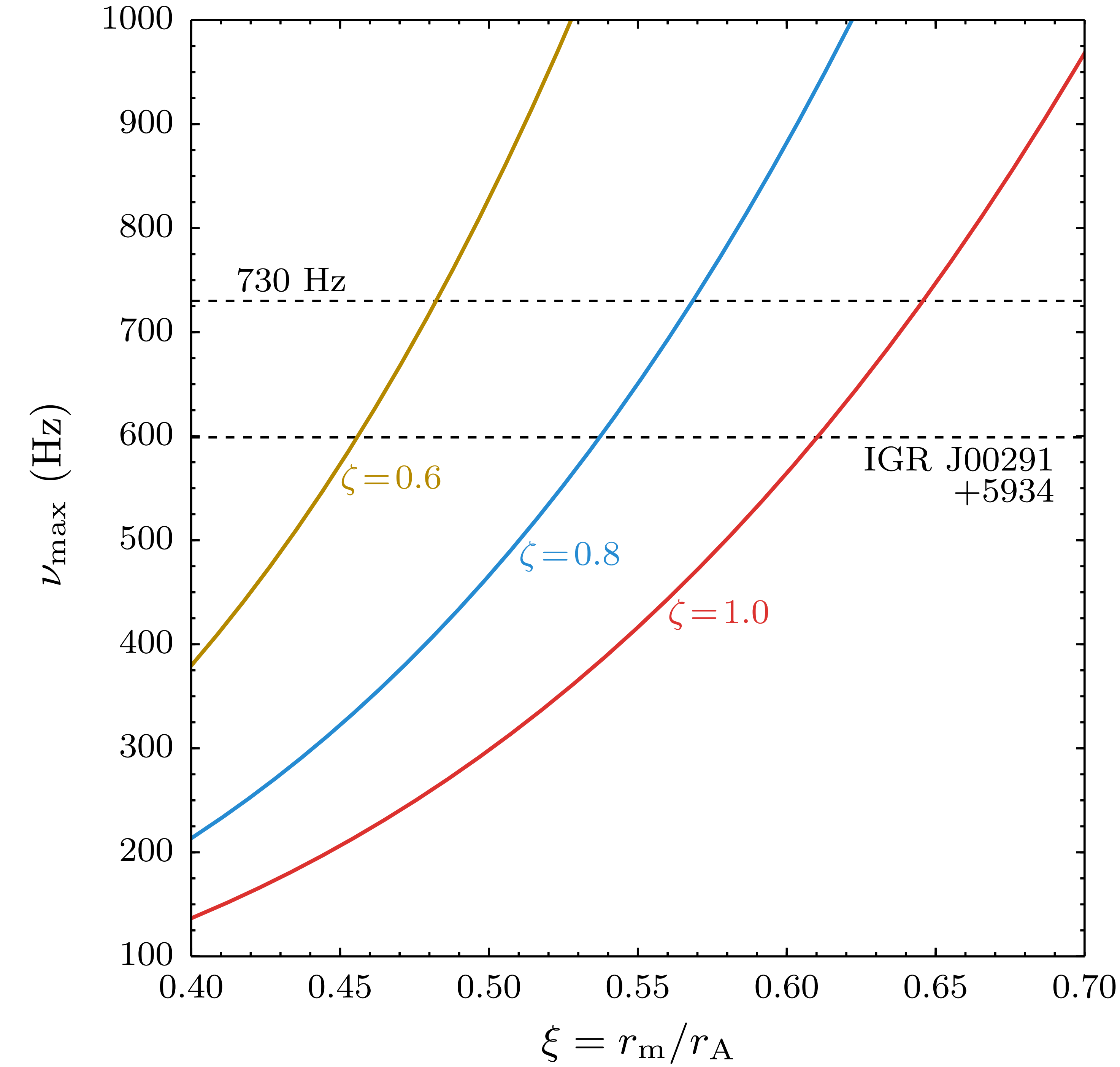
In spin equilibrium:

$$\frac{r_{\rm m}}{r_{\rm LC}} = 2^{-1/2}\frac{\xi^{7/2}}{\zeta^2}$$

To see channeled accretion:

$$r_{\rm m} > r_*$$



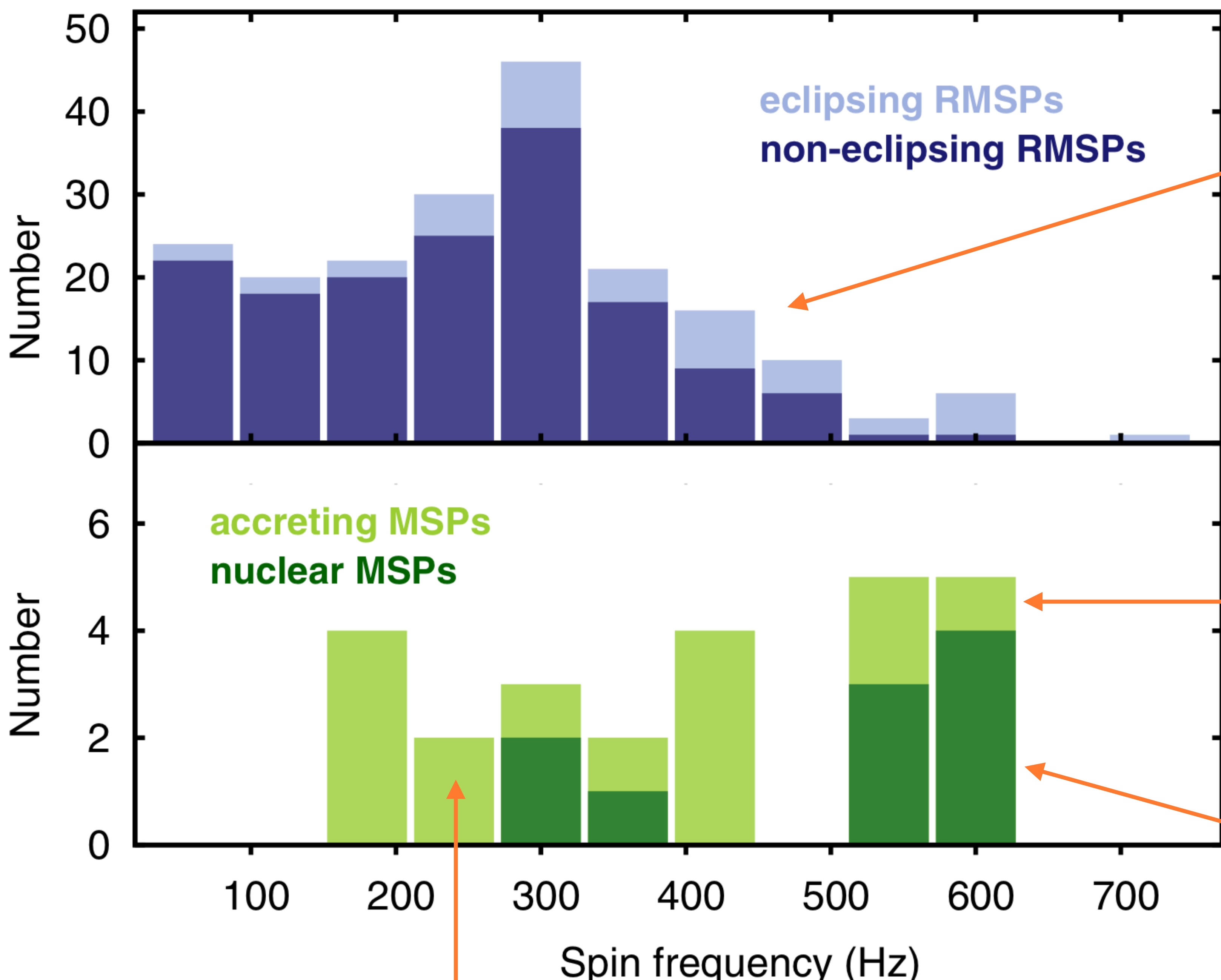


Max spin for accretion-powered MSPs:

$$\nu_{\rm max} = 3374\,\zeta^{-2}\xi^{7/2}\left(\frac{r_*}{10\,{\rm km}}\right)^{-1}\ {\rm Hz}$$

Independent of magnetic moment and accretion rate!

Papitto+ 2014



radio pulsars slower due to strong spin-down during RLDP?
e.g. Tauris 2012

ν_{max} gives AMSP cut-off?

nuclear sources similar if mag. moments not much smaller?

$\nu_{\rm eqlm}(\mu, \dot{M}, M)$ — gives flat-ish distribution?

Application 3: Jets

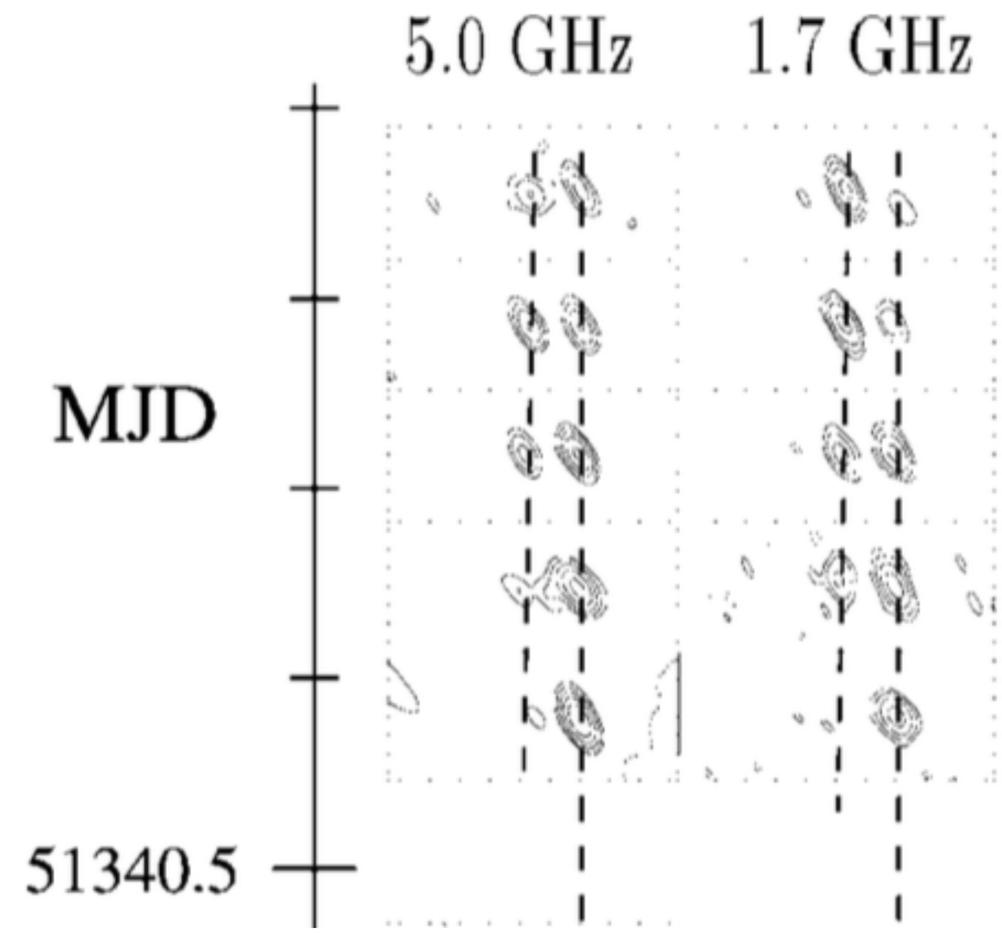
Sco X-1, Cir X-1 — $L_j > 10^{35}$ erg/s

Fomalont+ 2001, Fender+ 2004

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

$$\mu = 10^{26}\ {\rm G}$$
$$\text{for} \quad \nu = 300\ {\rm Hz}$$
$$\dot{M} = 0.5\, \dot{M}_{\rm Edd}$$

Sco X-1



Fomalont+ 2001

$L_{\rm j} \propto \dot{M}^{4/7}$ — similar to Aql X-1 [modulo $L_j(L_R)$]

— not similar to 4U 1728-34

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

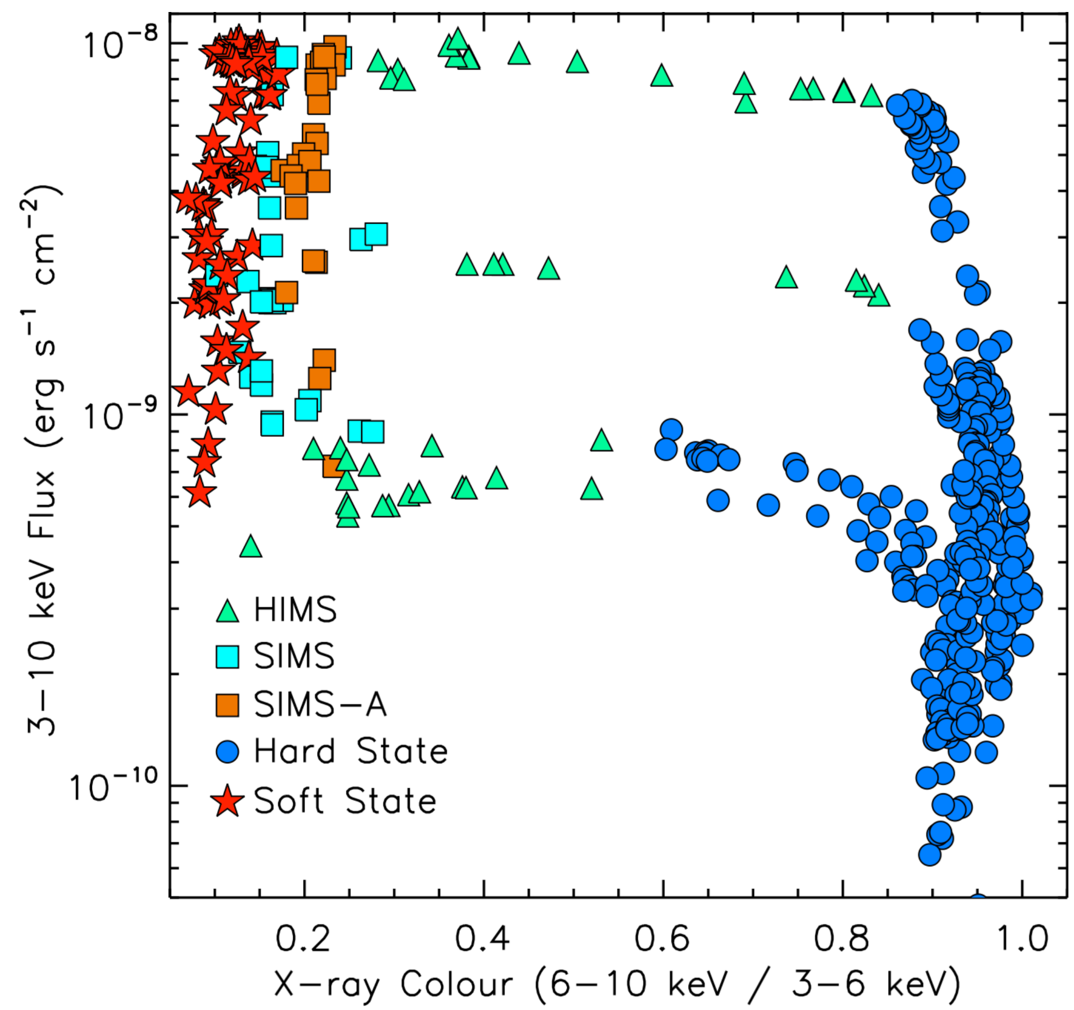
e.g. Aql X-1 Tudose+ 2009, Miller-Jones+ 2010

but not others (most?) Migliari & Fender 2006

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

$$\mu_{\rm crit} \sim \text{few} \times 10^{26}\ \text{G}$$

Black hole GX339-4



Plant+ 2014

Summary

- Differential rotation between star & disc may open nearly all the disc-coupling magnetic flux

- If opening is efficient, significant power can be tapped by high-spin, strongly magnetised objects — e.g. millisecond pulsars

- May be relevant for setting the torque on accreting MSPs in outburst, their spin distribution, and jets from high-spin neutron stars

- Can transitional MSPs help untangle some of the relationships between magnetic moment, accretion rate, torque, and radio emission?

- ApJ 822, 33 — analytic model & comparison to observations