Unleashing the (Electromagnetic) Beast

disk-induced field-line opening in accreting millisecond pulsars

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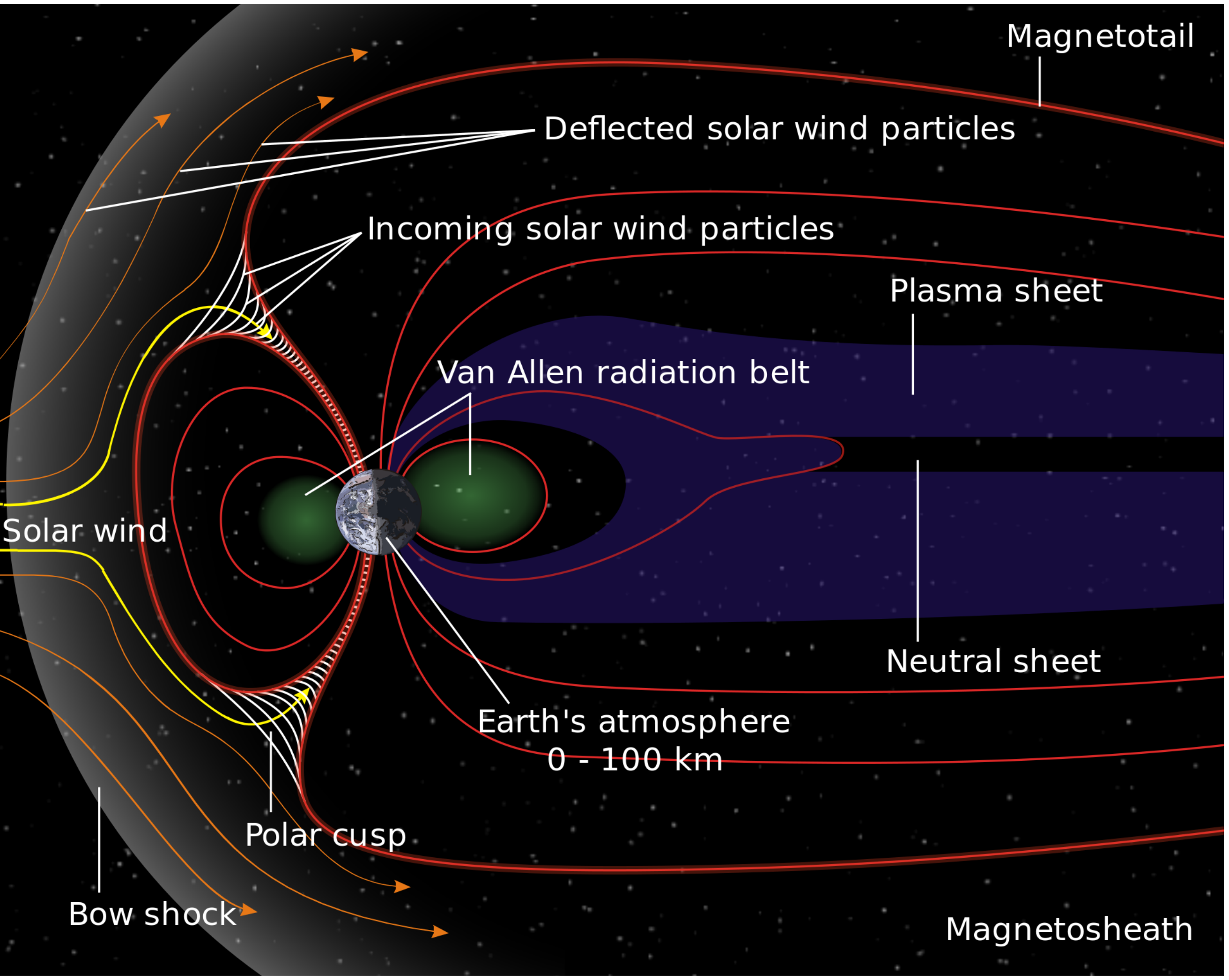
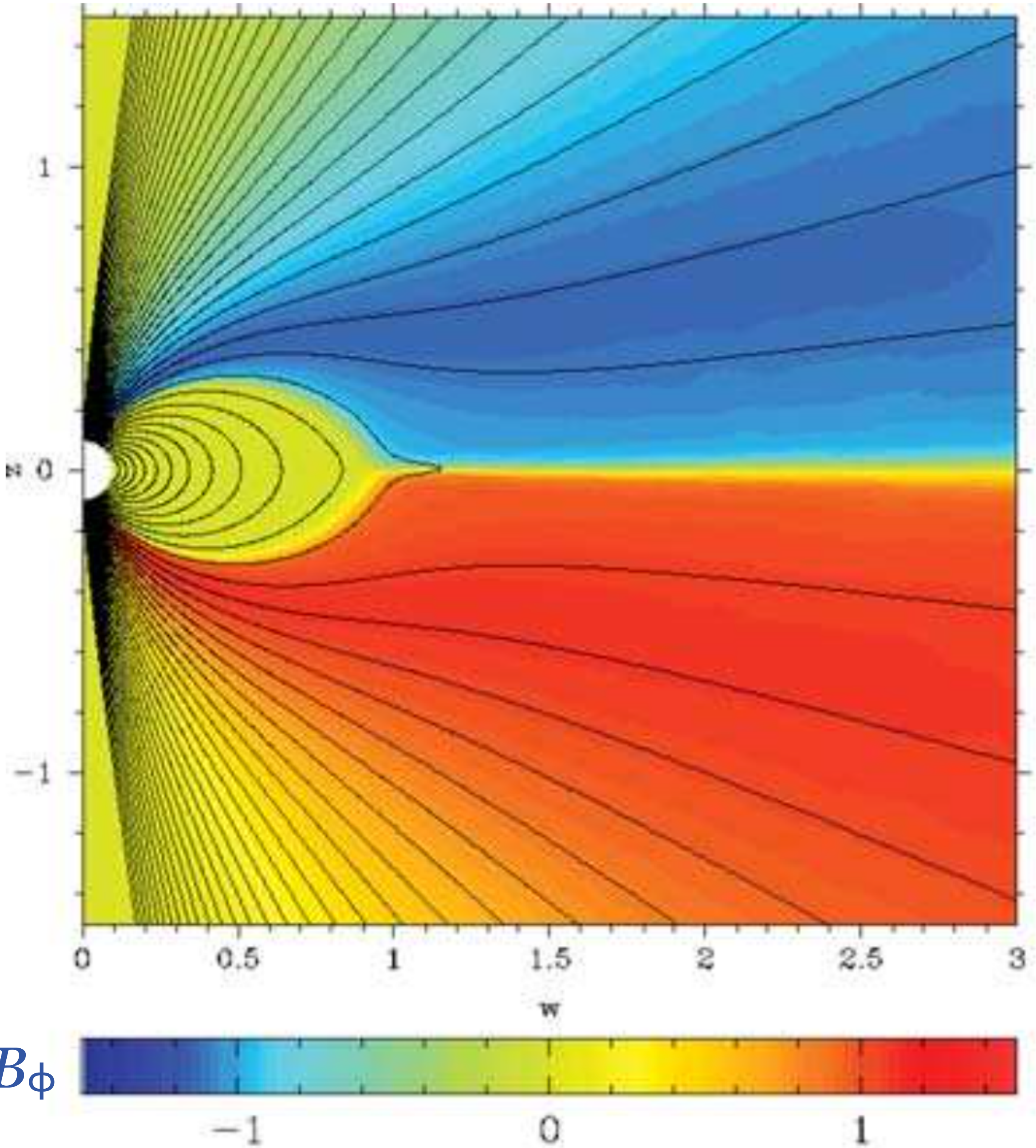
Earth



Pulsar



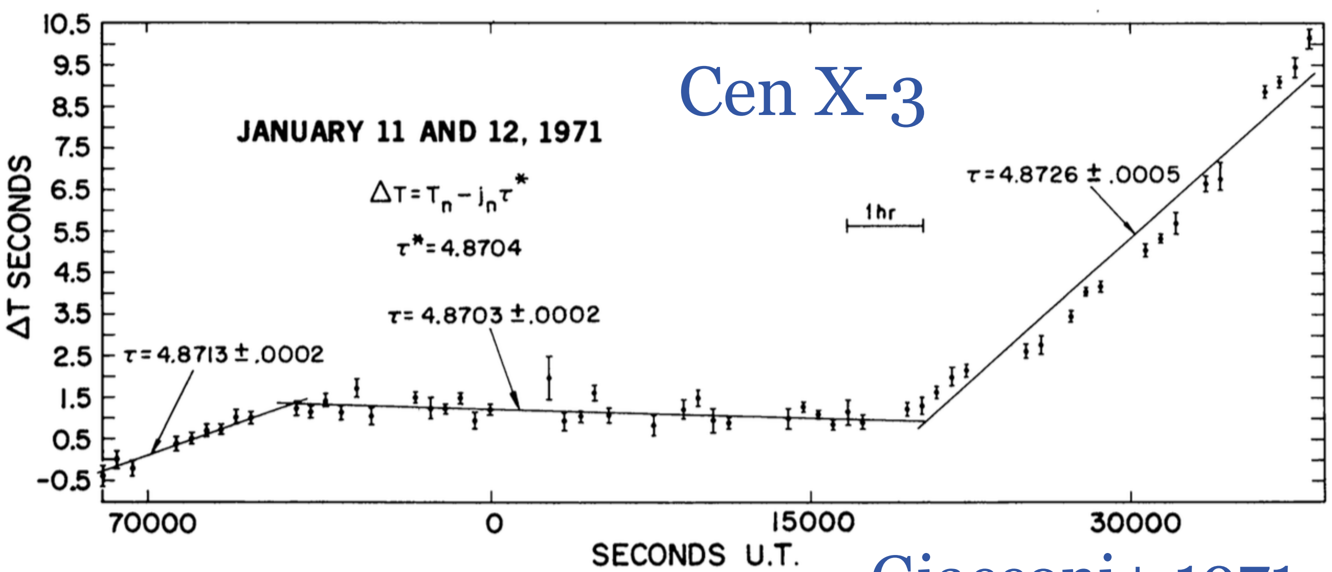
colour: B_ϕ

Komissarov 2006

Questions we're interested in

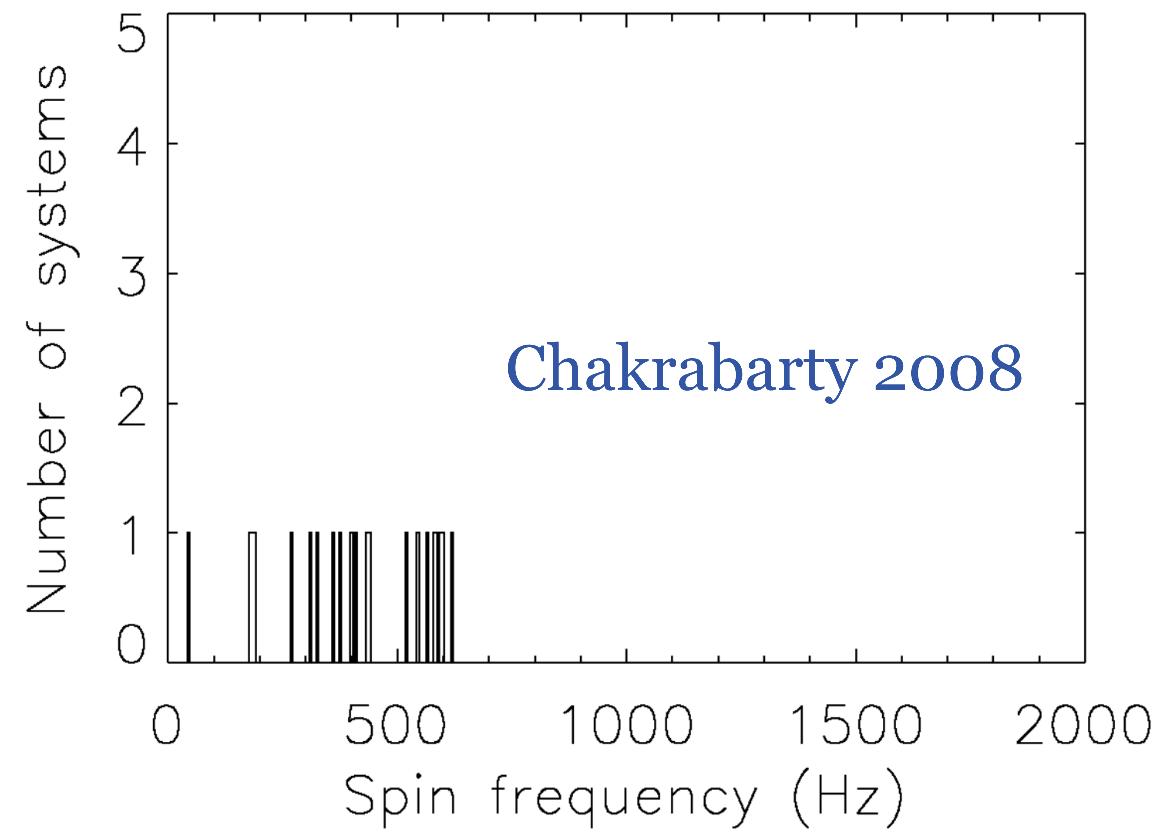
torques on accreting neutron stars

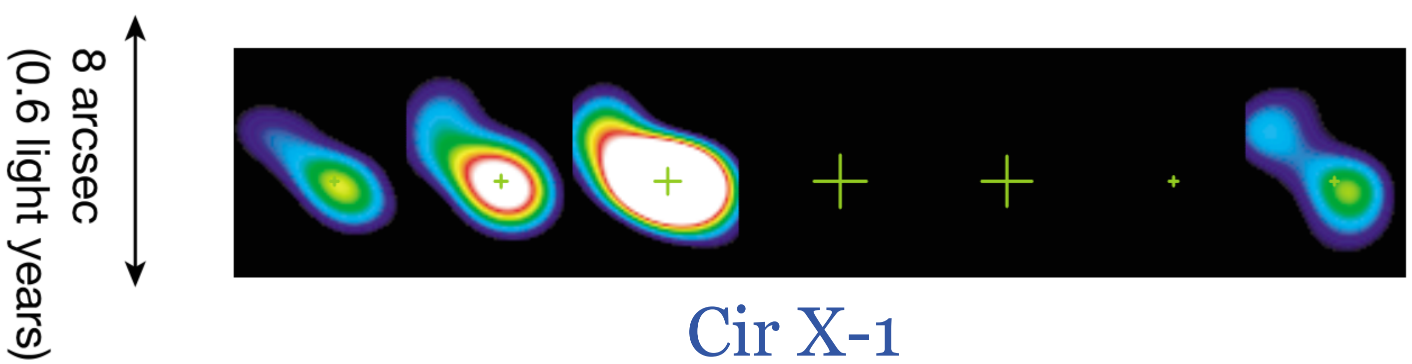
phase residuals



Giacconi+ 1971

spin cutoff of millisecond X-ray pulsars





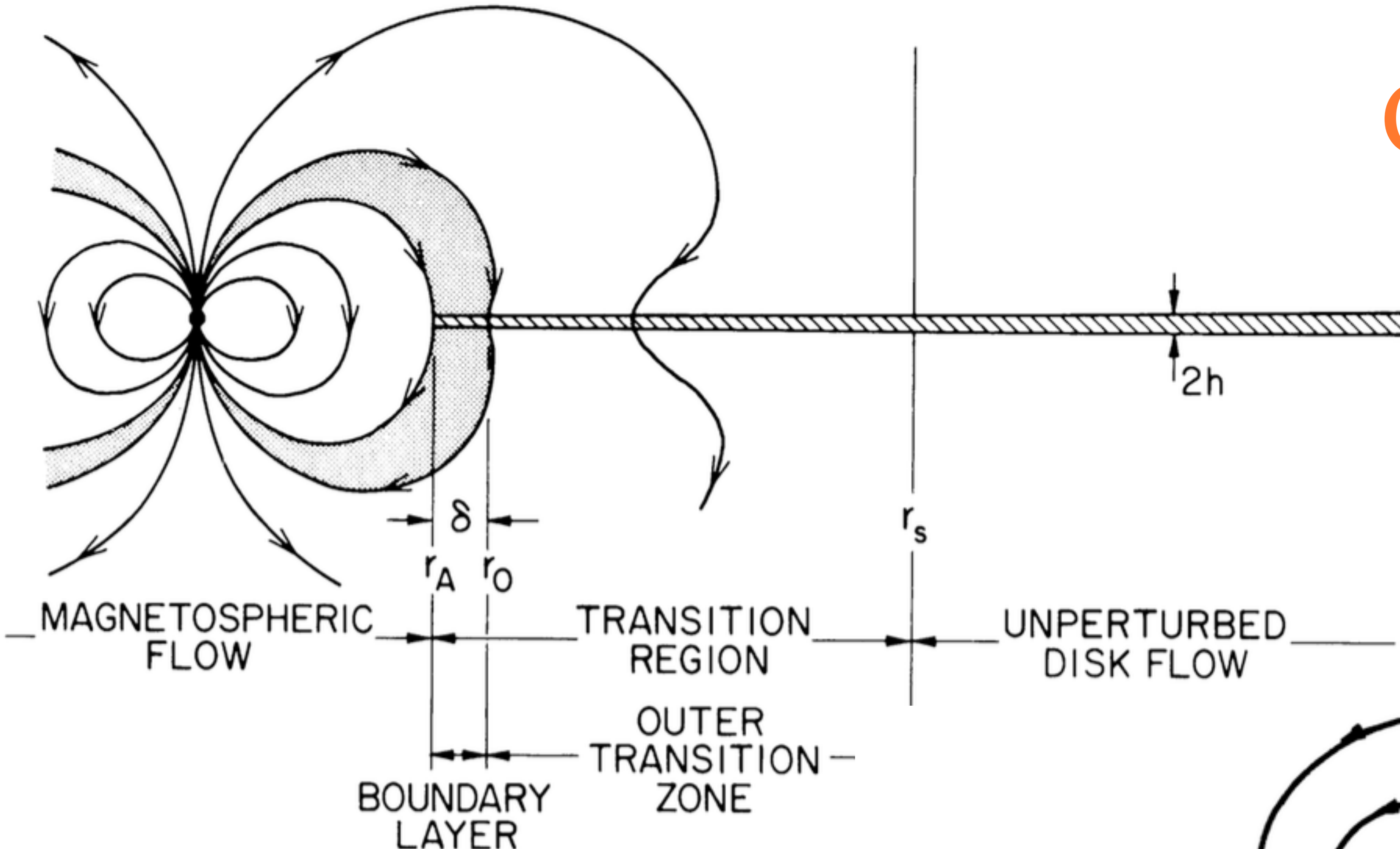
Cir X-1

neutron star jets

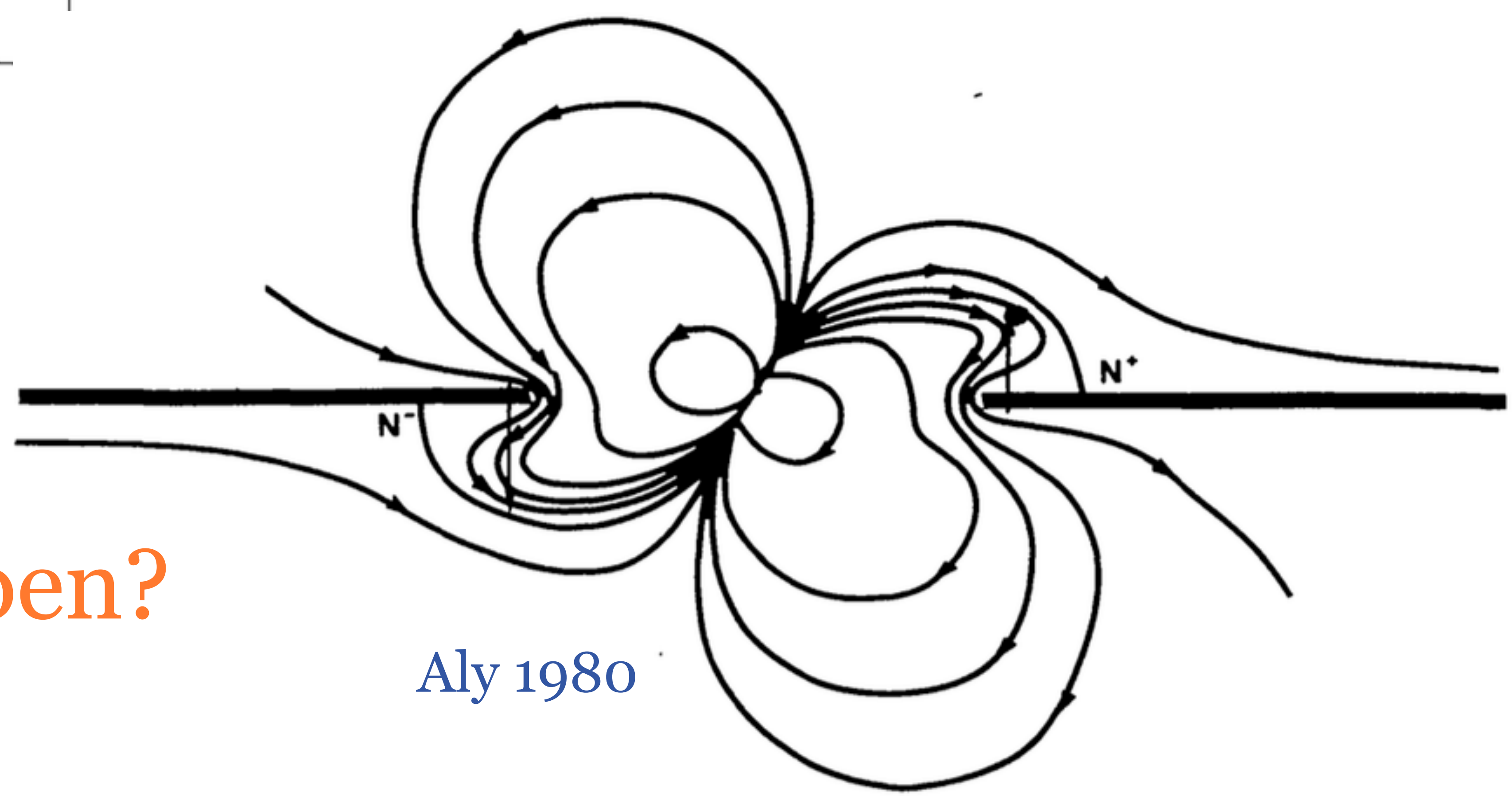
Fender+ 2004

Magnetospheric geometry

Closed…



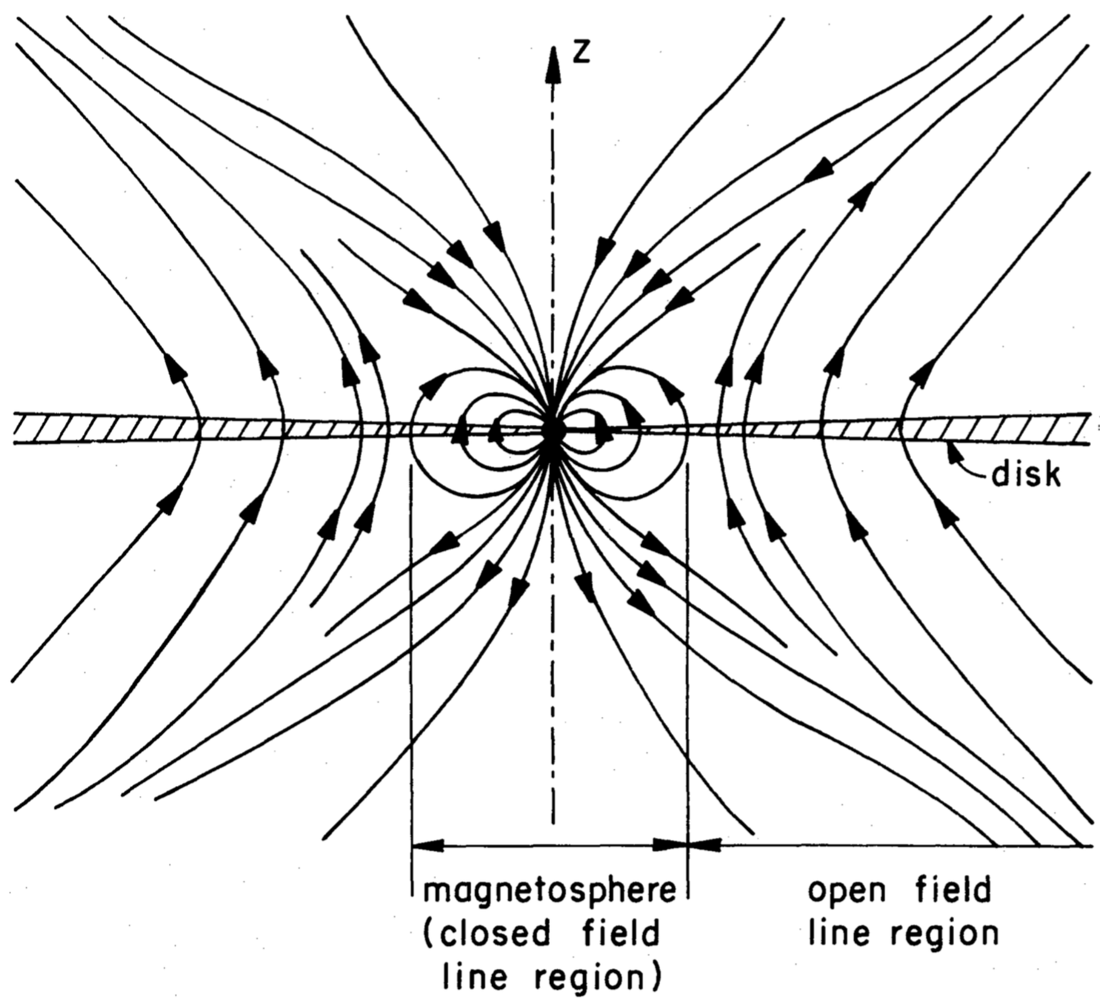
Ghosh & Lamb 1978



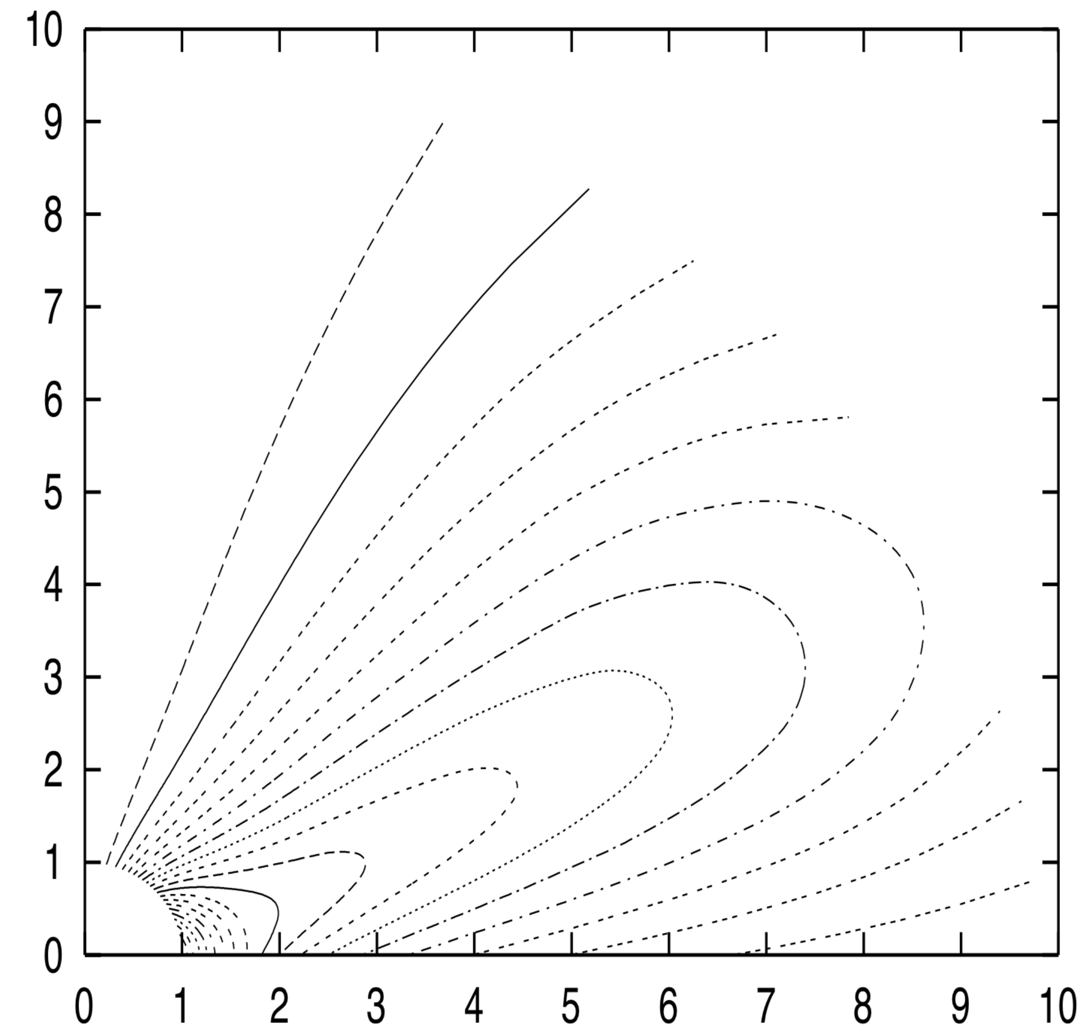
…or open?

Aly 1980

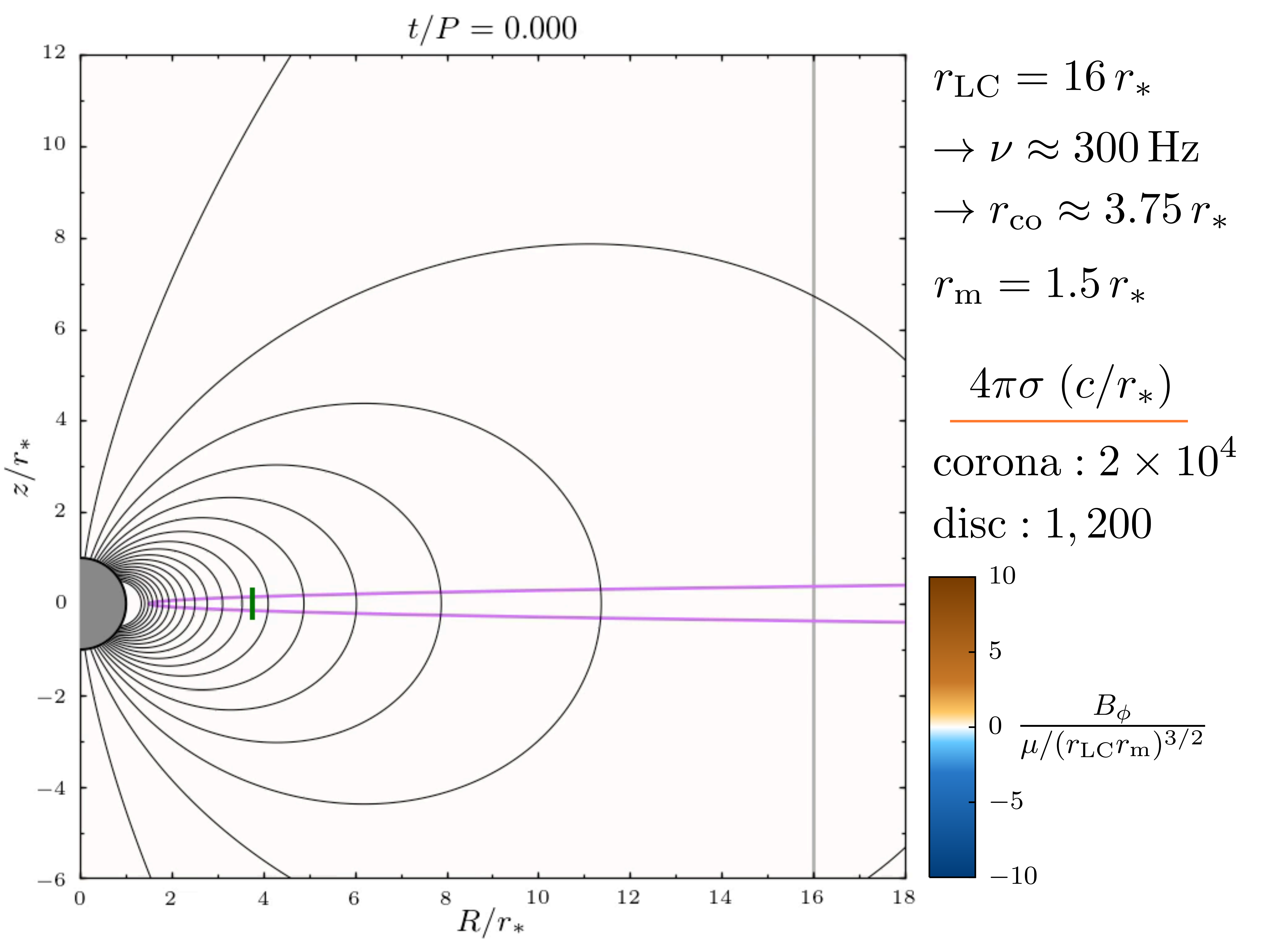
Field lines can be opened by disc



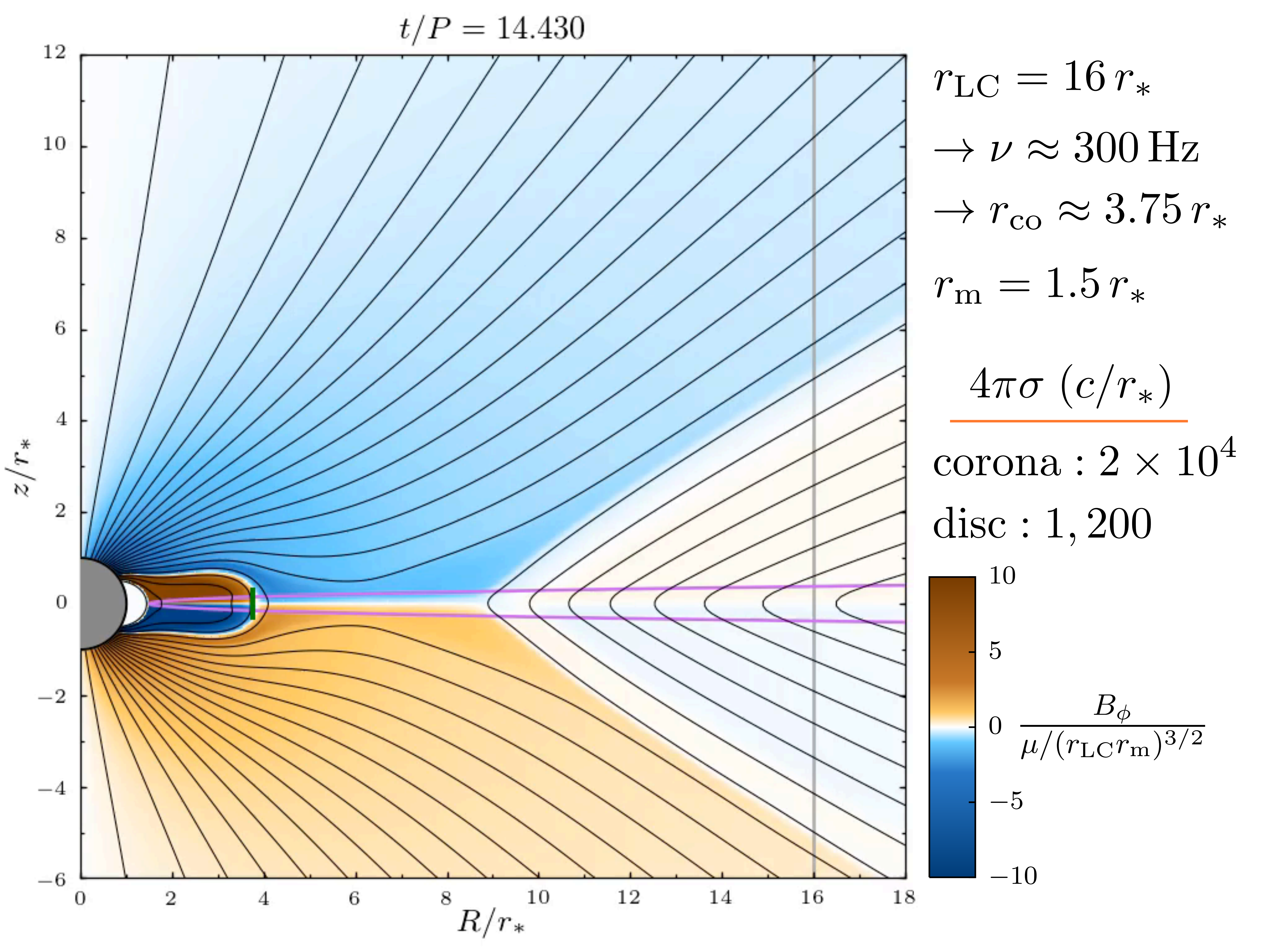
Lovelace, Romanova,
Bisnovatyi-Kogan 1995



Uzdensky, Koenigl, Litwin 2002

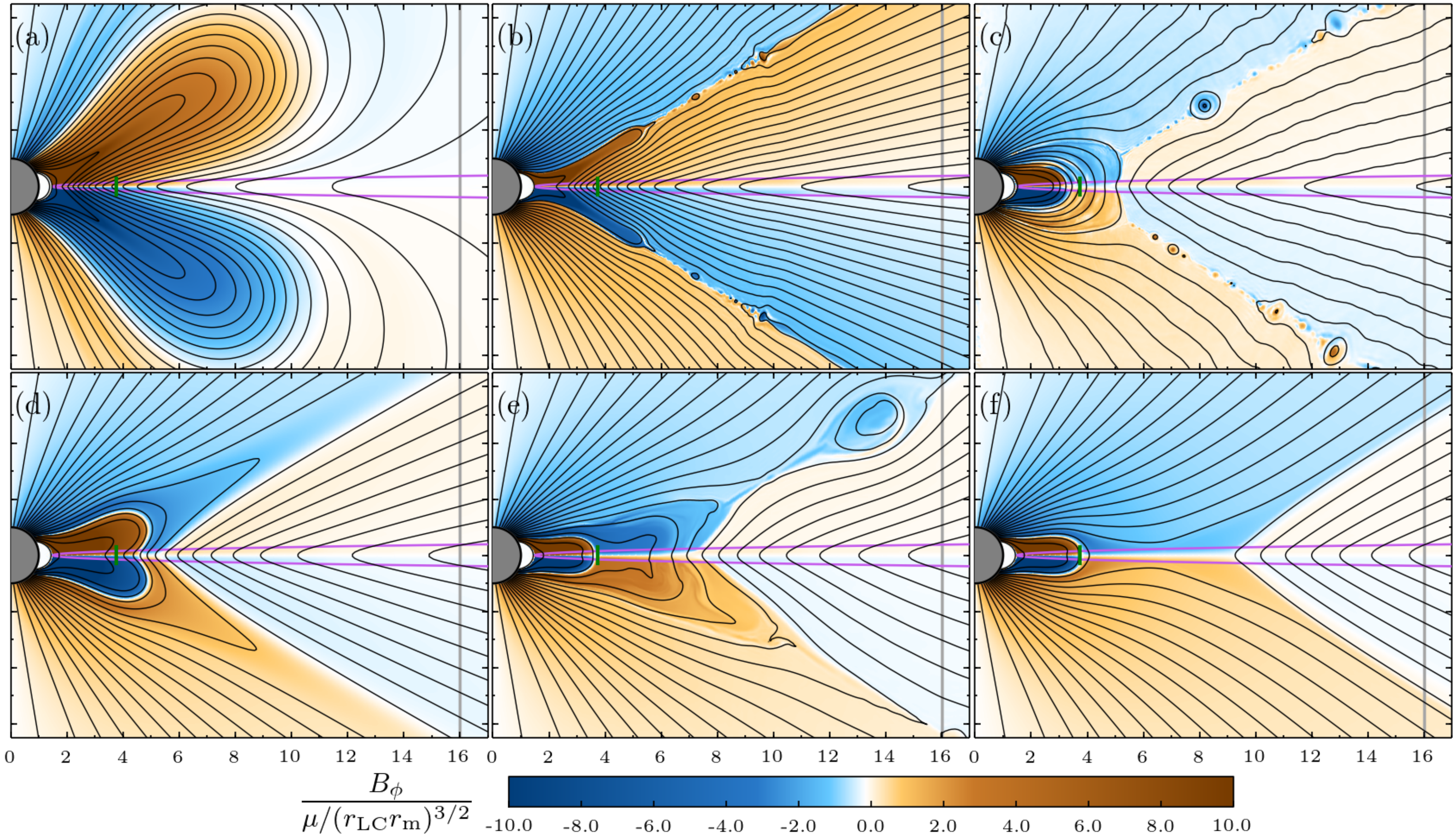


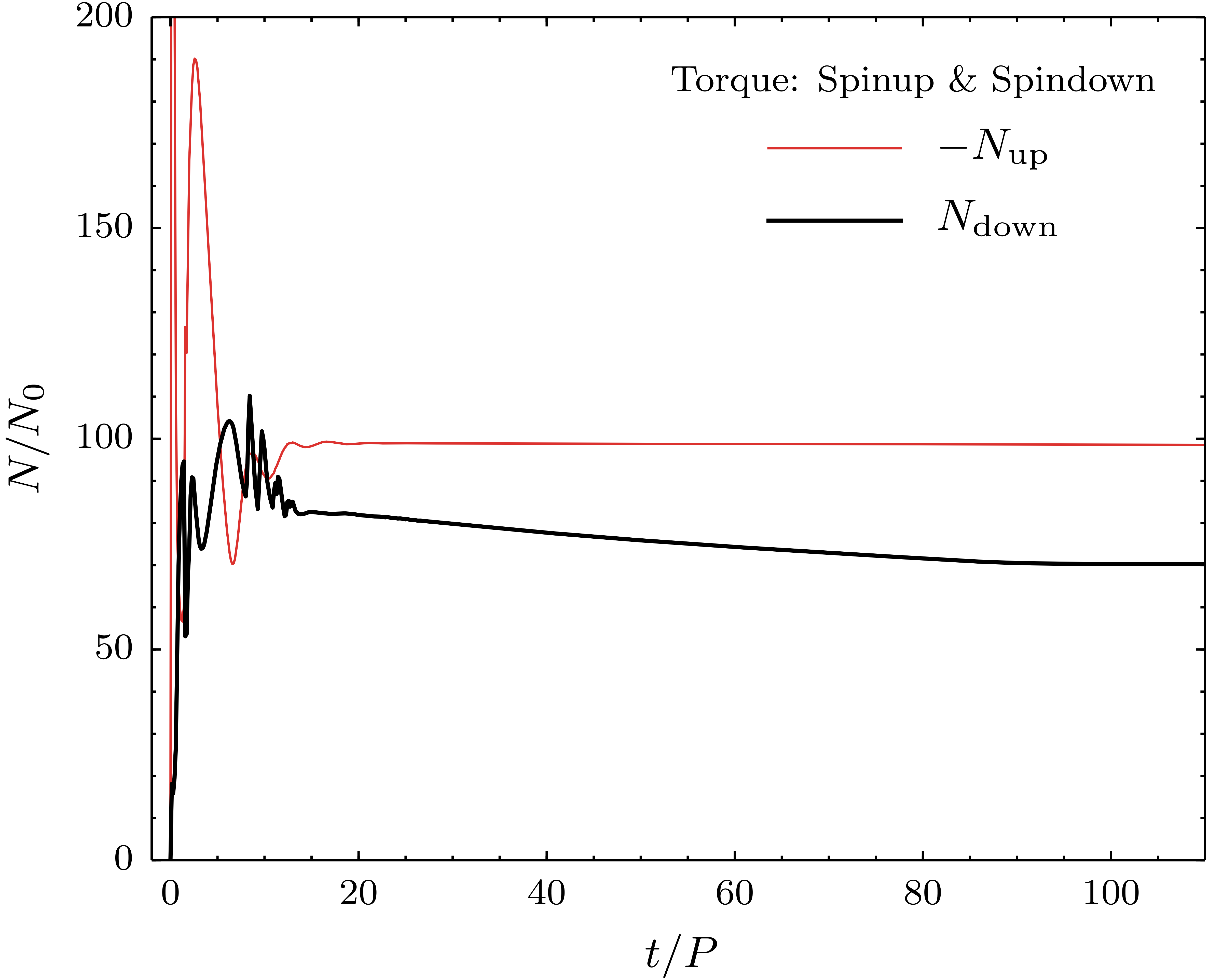
$t/P = 0.000$
z/r_*
R/r_*
$r_{\mathrm{LC}} = 16\, r_*$
$\rightarrow \nu \approx 300\,\mathrm{Hz}$
$\rightarrow r_{\mathrm{co}} \approx 3.75\, r_*$
$r_{\mathrm{m}} = 1.5\, r_*$
$4\pi\sigma\ (c/r_*)$
corona : 2×10^4
disc : $1,200$
$\frac{B_\phi}{\mu/(r_{\mathrm{LC}} r_{\mathrm{m}})^{3/2}}$



$t/P = 14.430$
z/r_*
R/r_*
$r_{\rm LC} = 16\, r_*$
$\rightarrow \nu \approx 300\,{\rm Hz}$
$\rightarrow r_{\rm co} \approx 3.75\, r_*$
$r_{\rm m} = 1.5\, r_*$
$4\pi\sigma\ (c/r_*)$
corona : 2×10^4
disc : $1,200$
$\frac{B_\phi}{\mu/(r_{\rm LC} r_{\rm m})^{3/2}}$

Opening, reconnection, relaxation





Torque: Spinup & Spindown
$-N_{\rm up}$
$N_{\rm down}$
N/N_0
t/P
0
50
100
150
200
0
20
40
60
80
100

Include radial velocity in disc

Use more complete disc model with, e.g.:

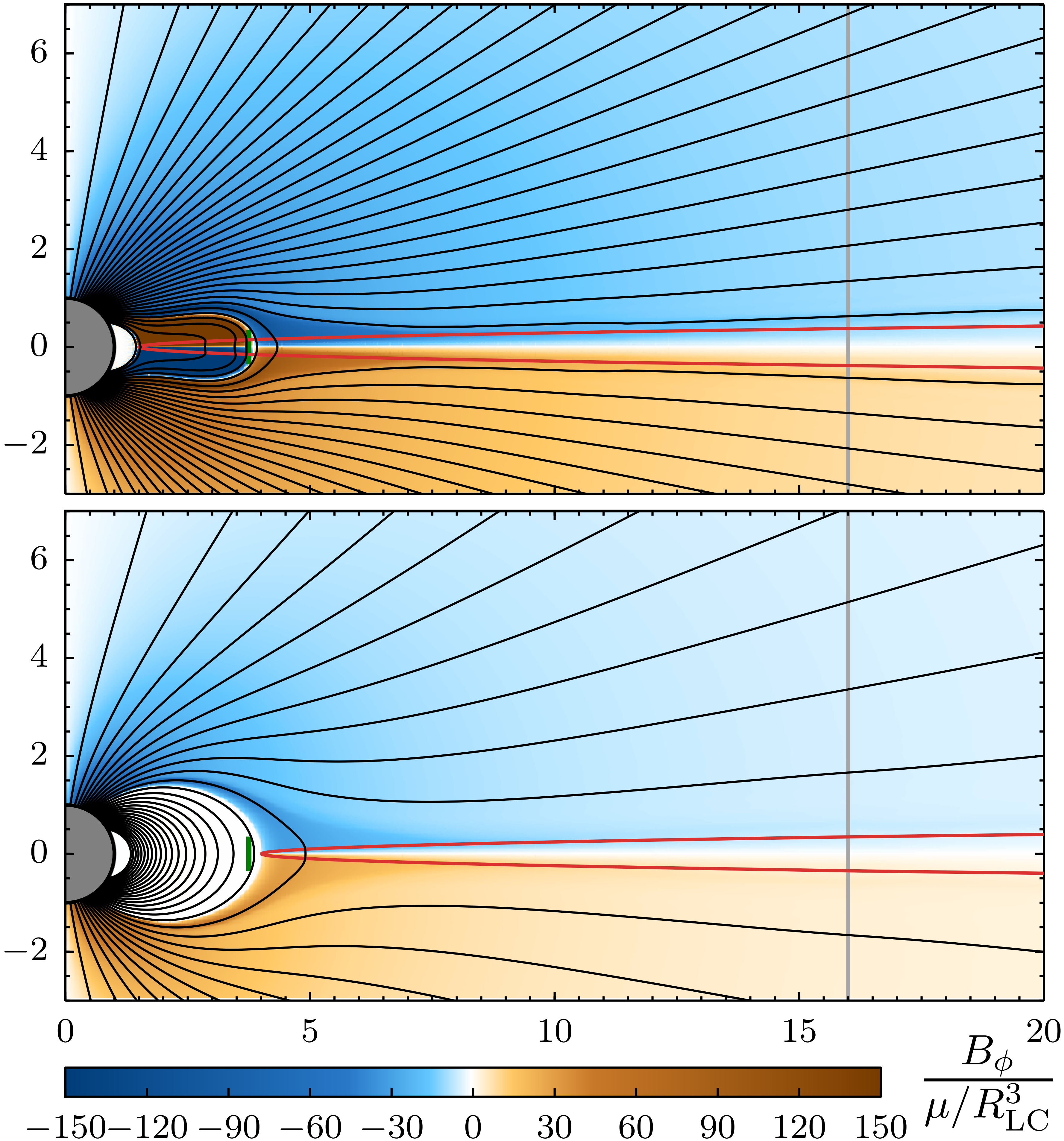
$$\alpha_{\rm SS} = 0.4 \qquad r_{\rm m} = 1.5\, r_* \qquad r_{\rm LC} = 16\, r_*$$

$$\mathrm{Pr}_{\rm m} = \frac{\nu_{\rm turb}}{\eta_{\rm turb}} = 1$$

giving ~ self-consistent disc accretion velocity

	$N_{\rm spindown}/N_0$
With radial disc velocity:	82.21
Without radial velocity:	82.49

Steady States



$r_{\rm m} = 1.5\, r_*$

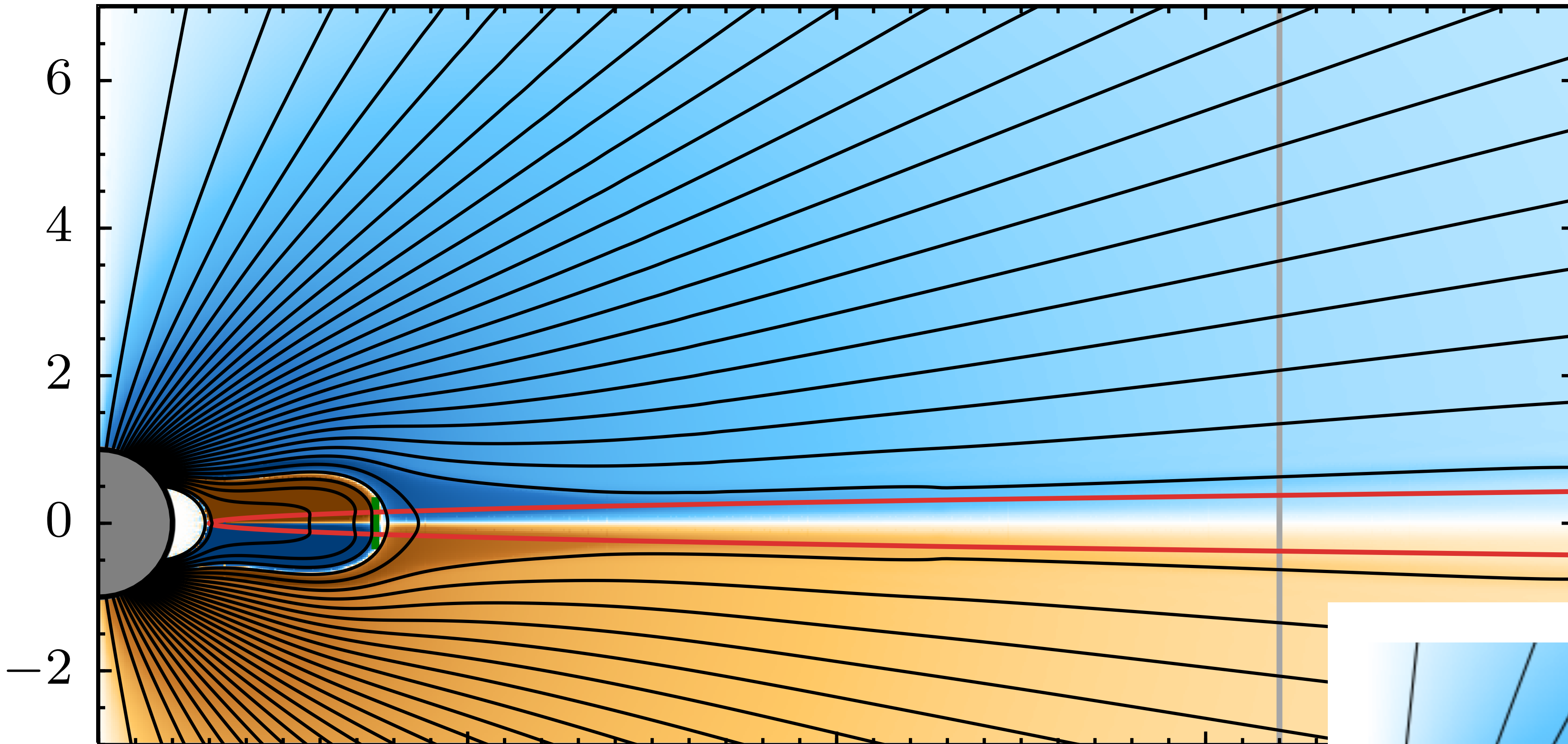
"accreting"

$4\pi\sigma_{\rm disc} = 1{,}600\, c/r_*$

$r_{\rm m} = 4.0\, r_*$

"propeller regime"

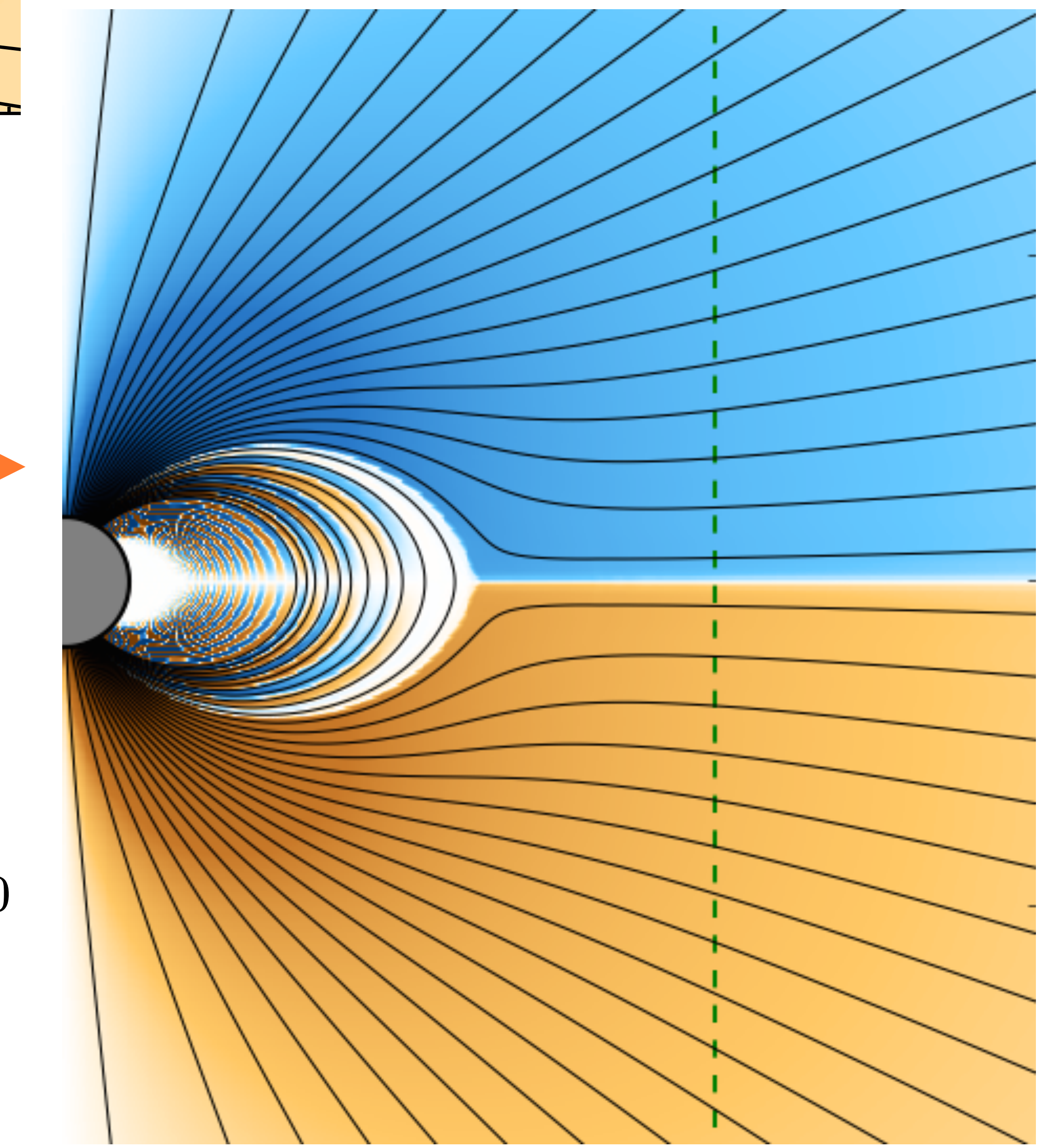
Steady States



$r_{\mathrm{m}} = 1.5\, r_*$

"accreting"

Looks like isolated pulsar →

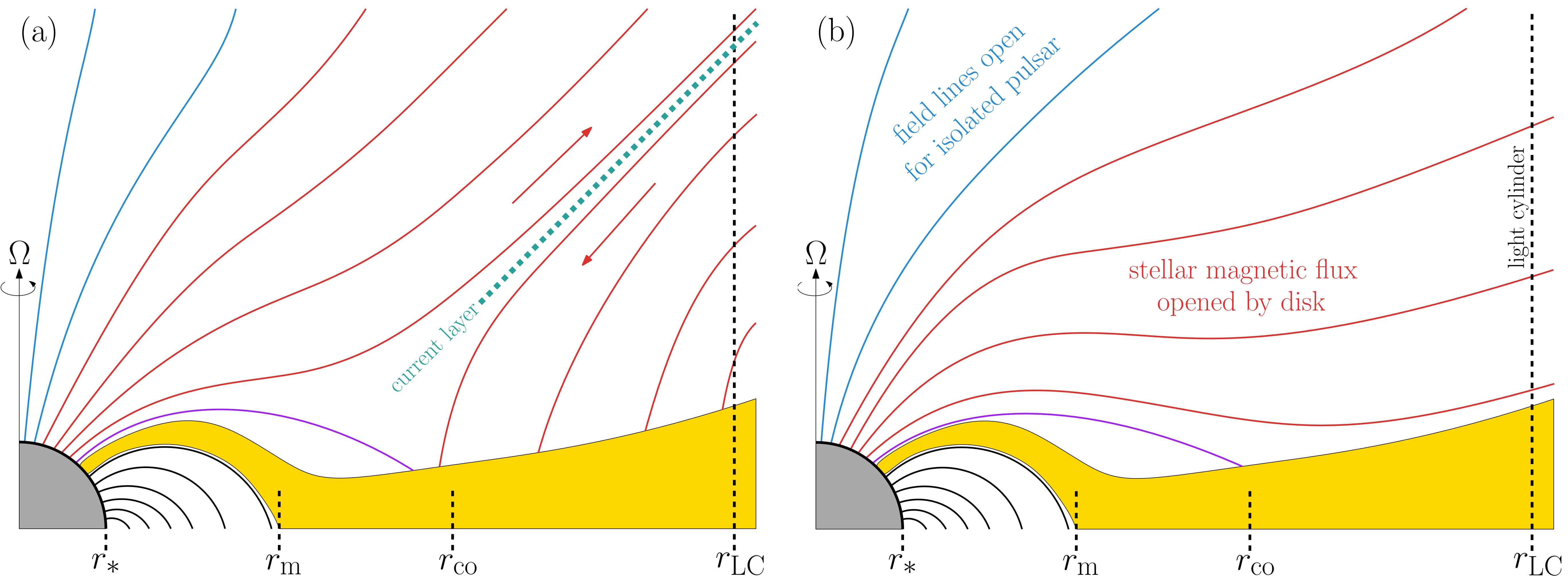


...but with more open flux

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

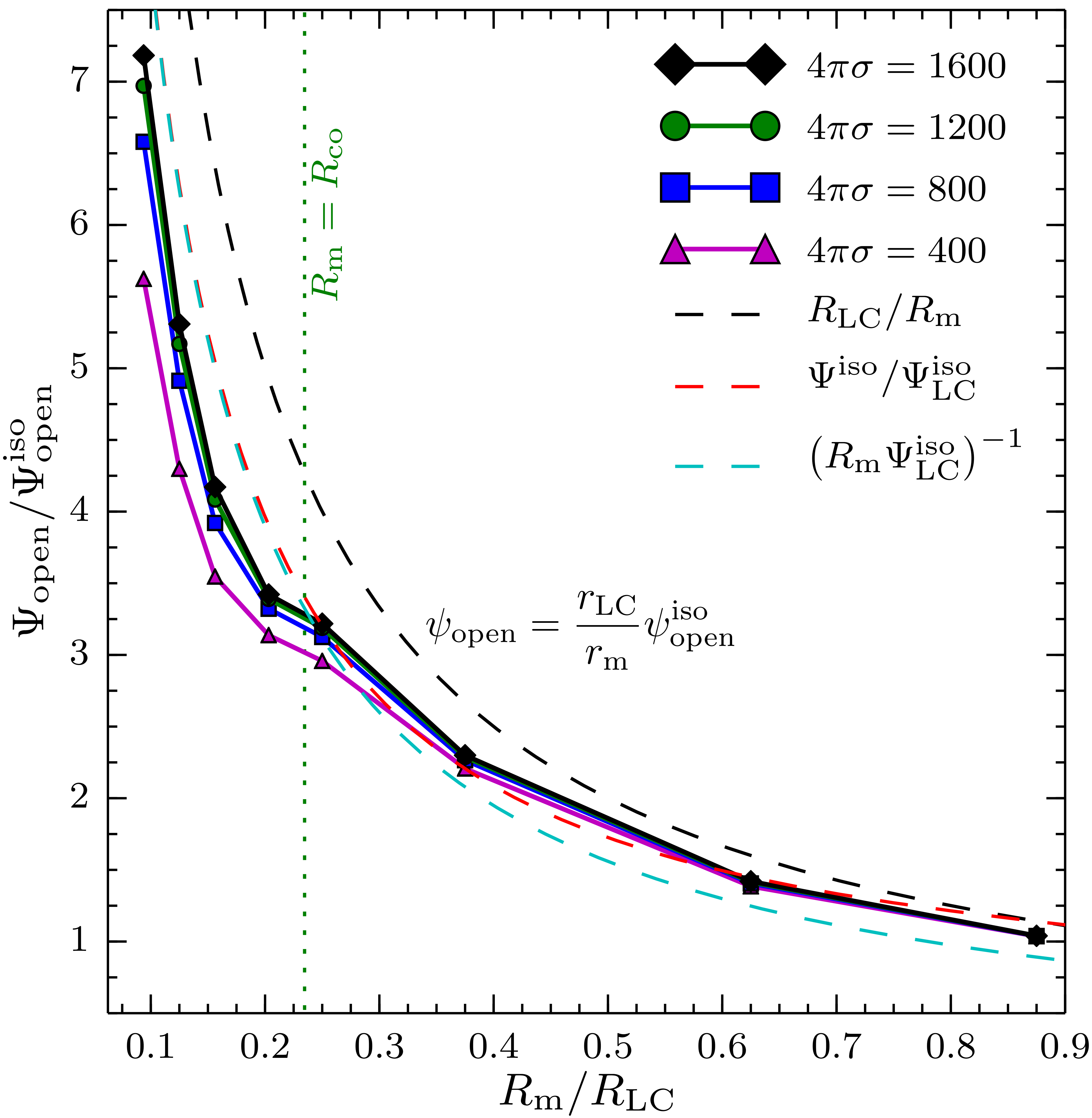
A toy model

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

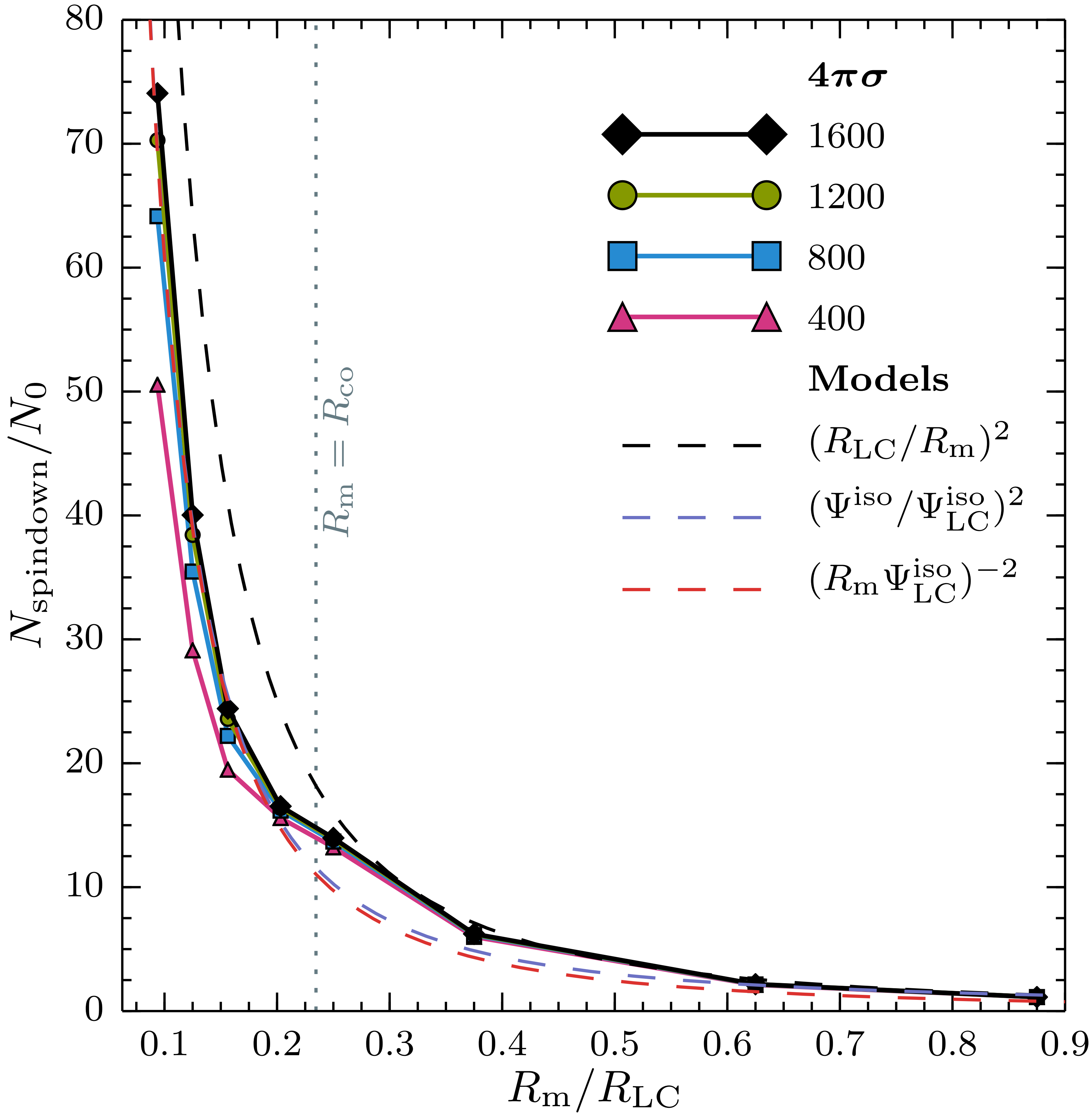


Parfrey, Spitkovsky, Beloborodov 2015

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



$4\pi\sigma = 1600$
$4\pi\sigma = 1200$
$4\pi\sigma = 800$
$4\pi\sigma = 400$
$R_{\rm LC}/R_{\rm m}$
$\Psi^{\rm iso}/\Psi^{\rm iso}_{\rm LC}$
$\left(R_{\rm m}\Psi^{\rm iso}_{\rm LC}\right)^{-1}$
$R_{\rm m} = R_{\rm co}$
$\psi_{\rm open} = \frac{r_{\rm LC}}{r_{\rm m}}\psi^{\rm iso}_{\rm open}$
$\Psi_{\rm open}/\Psi^{\rm iso}_{\rm open}$
$R_{\rm m}/R_{\rm LC}$
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2
3
4
5
6
7



$$N_{\rm spindown} \propto \psi^2_{\rm open}$$

total spin-down torque
vs
magnetospheric
radius

Simple model for torques...

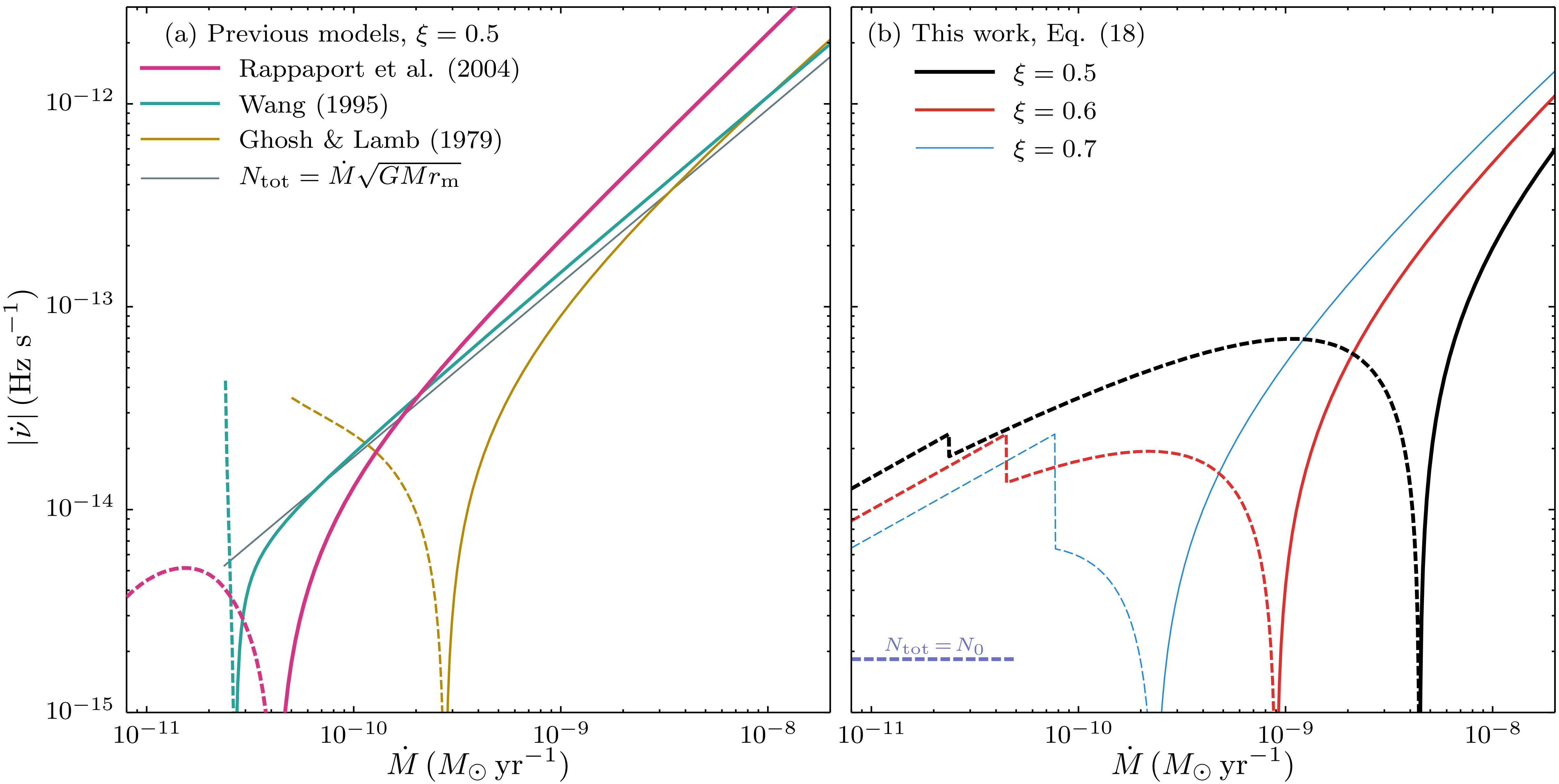
Isolated pulsar: $$L_0 = -N_0\Omega = \mu^2 \frac{\Omega^4}{c^3} \approx \frac{2}{3c}\Omega^2 \psi^2_{\rm open,0}$$

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

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

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

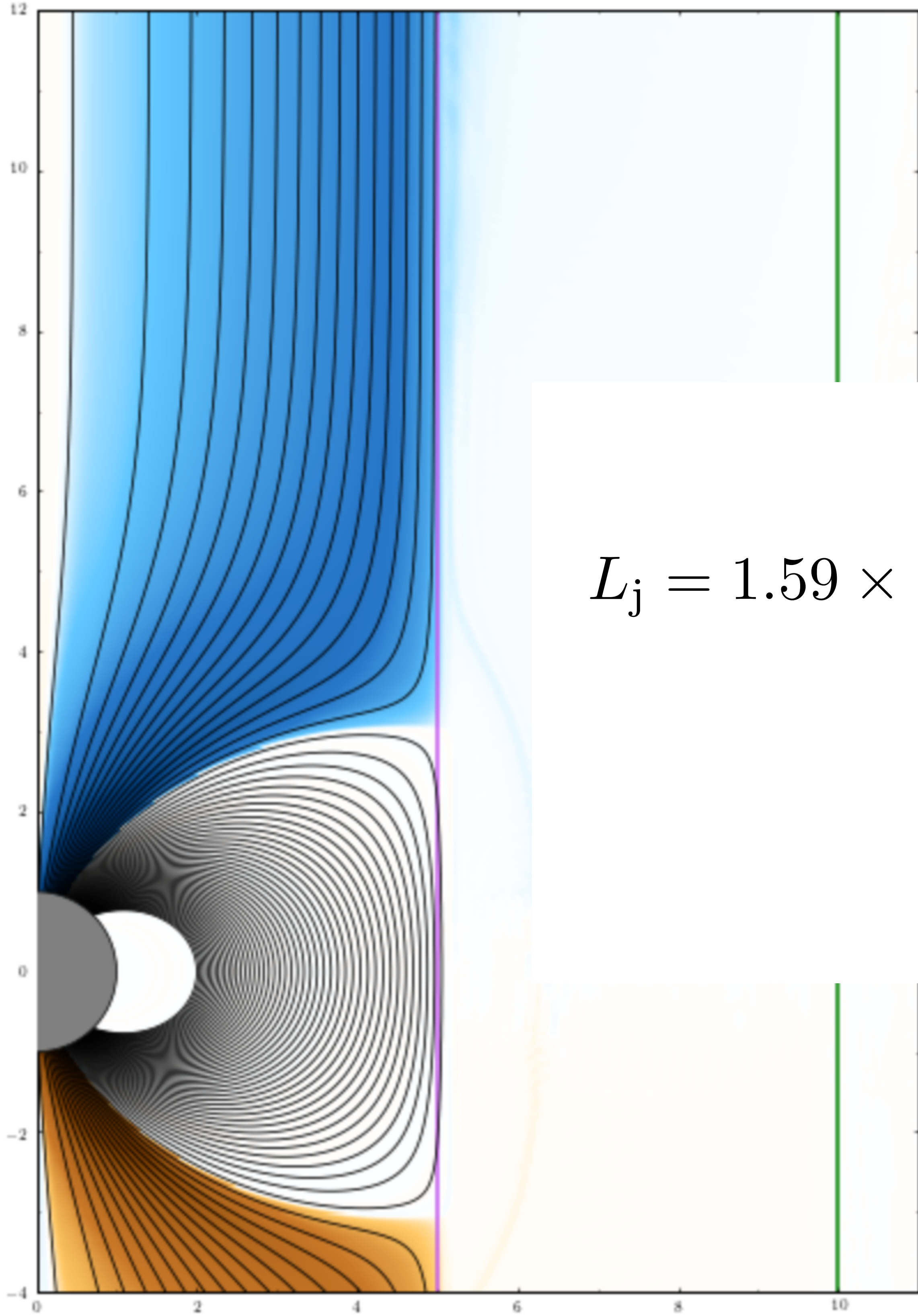
Torque models: 500 Hz, 10^8 G star



Parfrey, Spitkovsky, Beloborodov 2015

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

Jet power — if open flux is collimated



Scale with open flux in same way:

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

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

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

XTE J1814-338* $\xi < [0.72,\ 0.67,\ 0.61,\ 0.56]$ for $\zeta = [1.0,\ 0.9,\ 0.8,\ 0.7]$

* assuming $B \sim 10^8$ G

No enhanced/anomalous spin-down needed for

XTE J1751-305 Papitto+ 2008, Riggio+ 2011

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

Spin equilibrium

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

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

↓

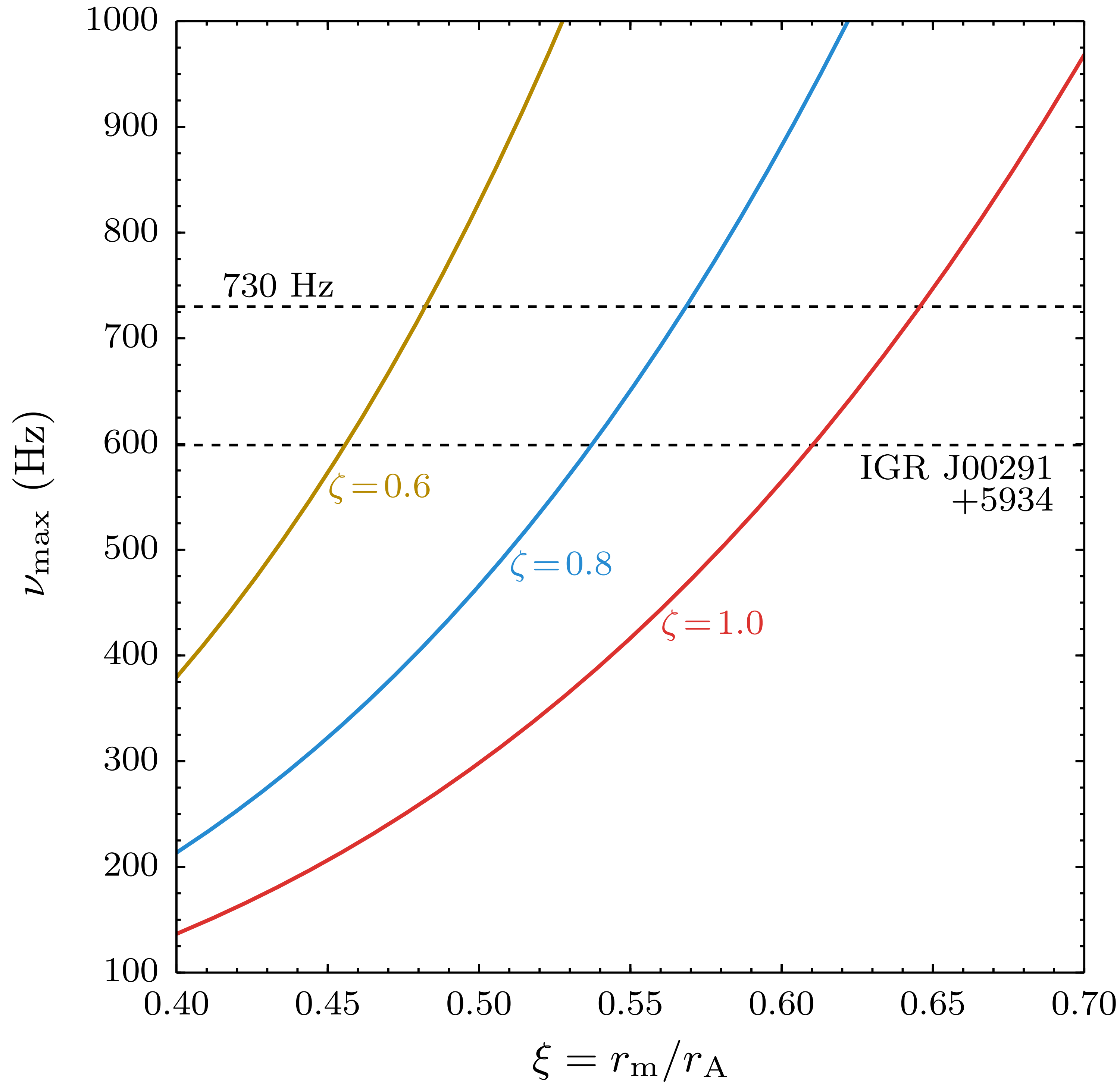
$$\nu_{\rm eqlm} = 956\,\zeta^{-2}\xi^{5/2}\left(\frac{\mu}{10^{26}\,{\rm G\,cm^3}}\right)^{-4/7} \times \left(\frac{M}{1.4\,M_\odot}\right)^{1/7}\left(\frac{\dot{M}}{10^{-10}\ M_\odot\,{\rm yr}^{-1}}\right)^{2/7}\ {\rm Hz}$$

In spin eqlm:

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

To see channeled accretion:

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

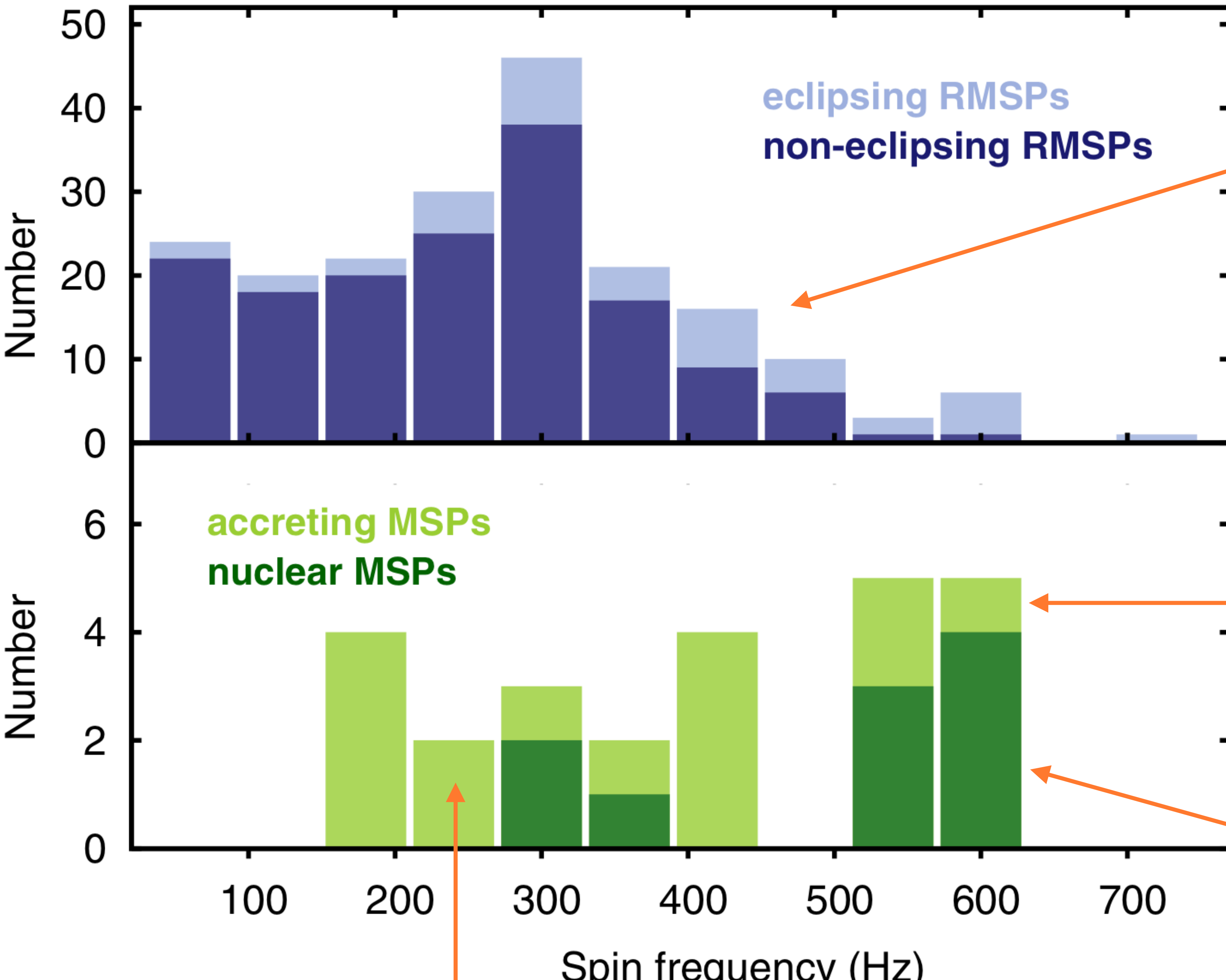


Max spin for AMSPs:

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

Independent of magnetic moment and accretion rate!

Papitto+ 2014



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

$\nu_{\max}$ gives AMSP cut-off?

nuclear sources similar if mag. moments not much smaller?

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

Jets

Fomalont+ 2001, Fender+ 2004

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

Model: $L_j = 4.6 \times 10^{35} (\zeta/\xi)^2 \, \mathrm{erg\,s^{-1}}$ for

$$\mu = 10^{26} \ \mathrm{G}$$
$$\nu = 300 \ \mathrm{Hz}$$
$$\dot{M} = 0.5 \, \dot{M}_{\mathrm{Edd}}$$

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

— not similar to 4U 1728-34

May explain why see soft state quenching in some sources

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

but not others (most?) Migliari & Fender 2006

→ critical μ for $r_m \to r_*$ at $\dot{M}_{\mathrm{Edd}}$: $\mu_{\mathrm{crit}} \sim \mathrm{few} \times 10^{26}$ G

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 AMSPs 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?

- Paper at arXiv:1507.08627 — comments welcome