Dead discs and unstable accretion bursts: magnetospheric accretion at low luminosities

Caroline D’Angelo, Unversity of Amsterdam

ESAC Colloquium

Thursday January 23, 2014

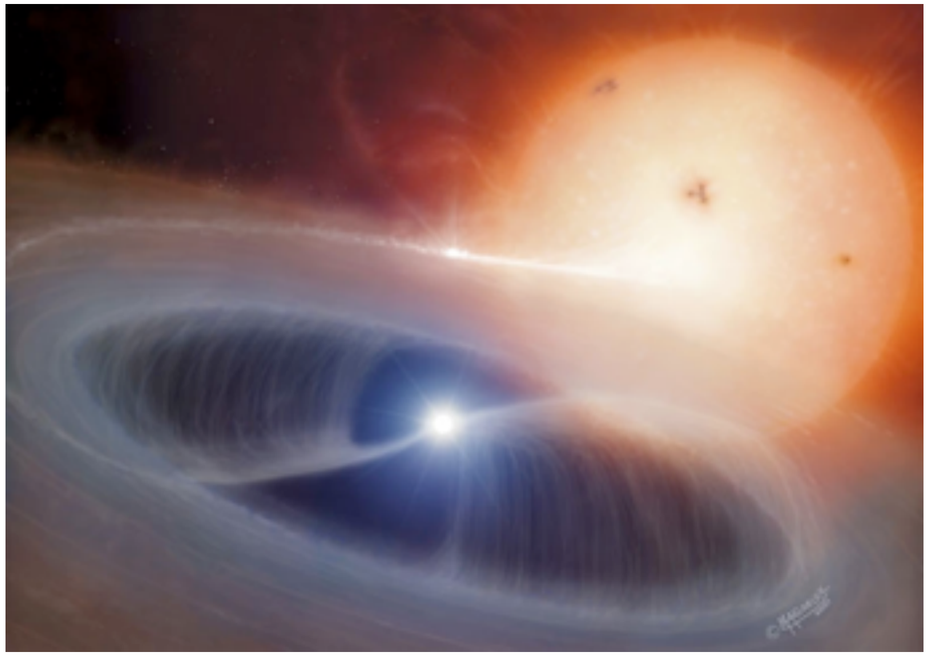
UNIVERSITY OF AMSTERDAM

NWO
Nederlandse Organisatie voor Wetenschappelijk Onderzoek

ASTRONOMICAL INSTITUTE
ANTON PANNEKOEK

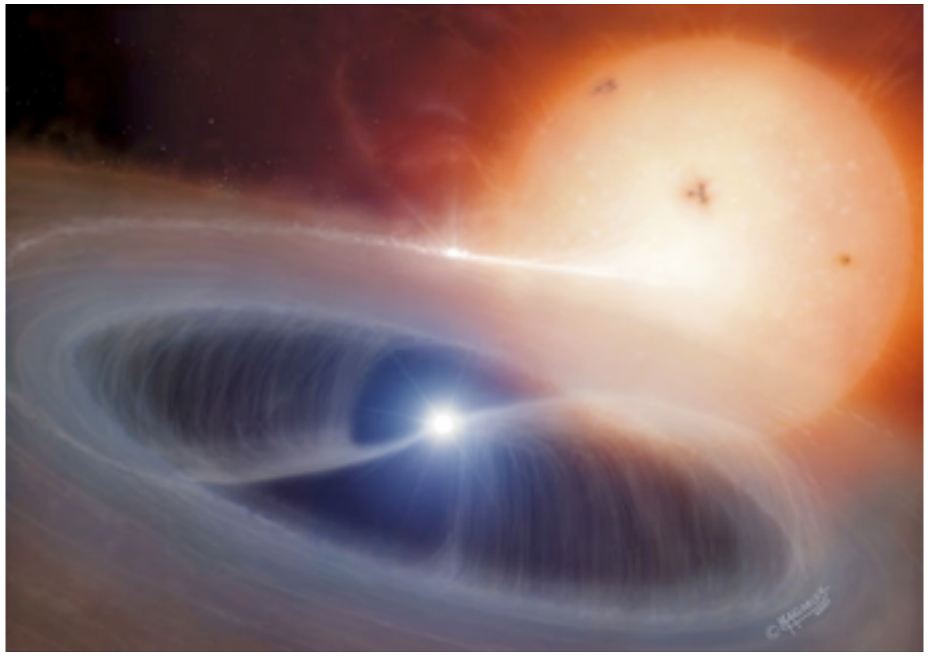
Strong stellar magnetic fields interacting with matter

Strong stellar magnetic fields interacting with matter

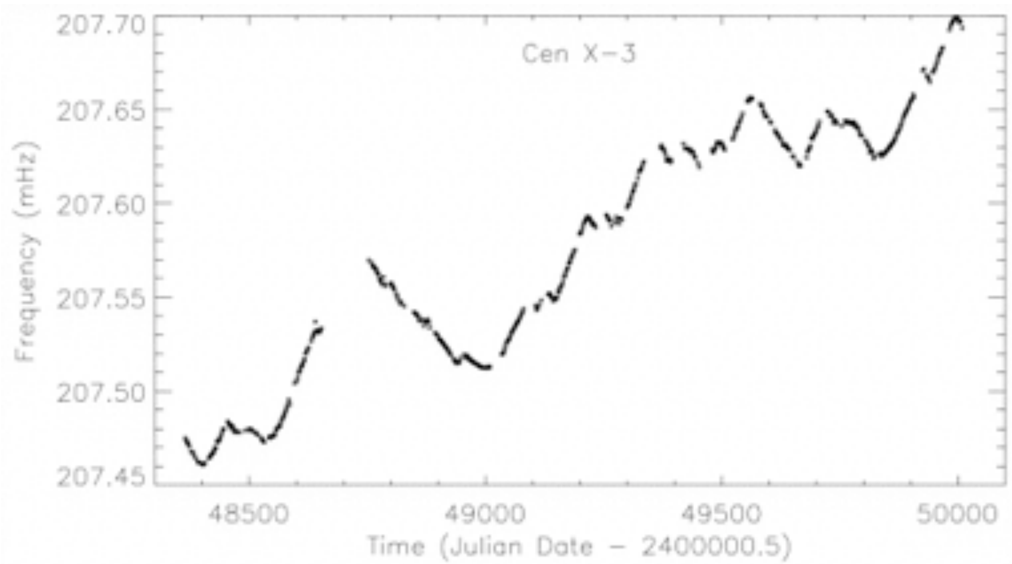


Coherent X-ray pulsations
(0.0025-100s) in accreting NS

Strong stellar magnetic fields interacting with matter

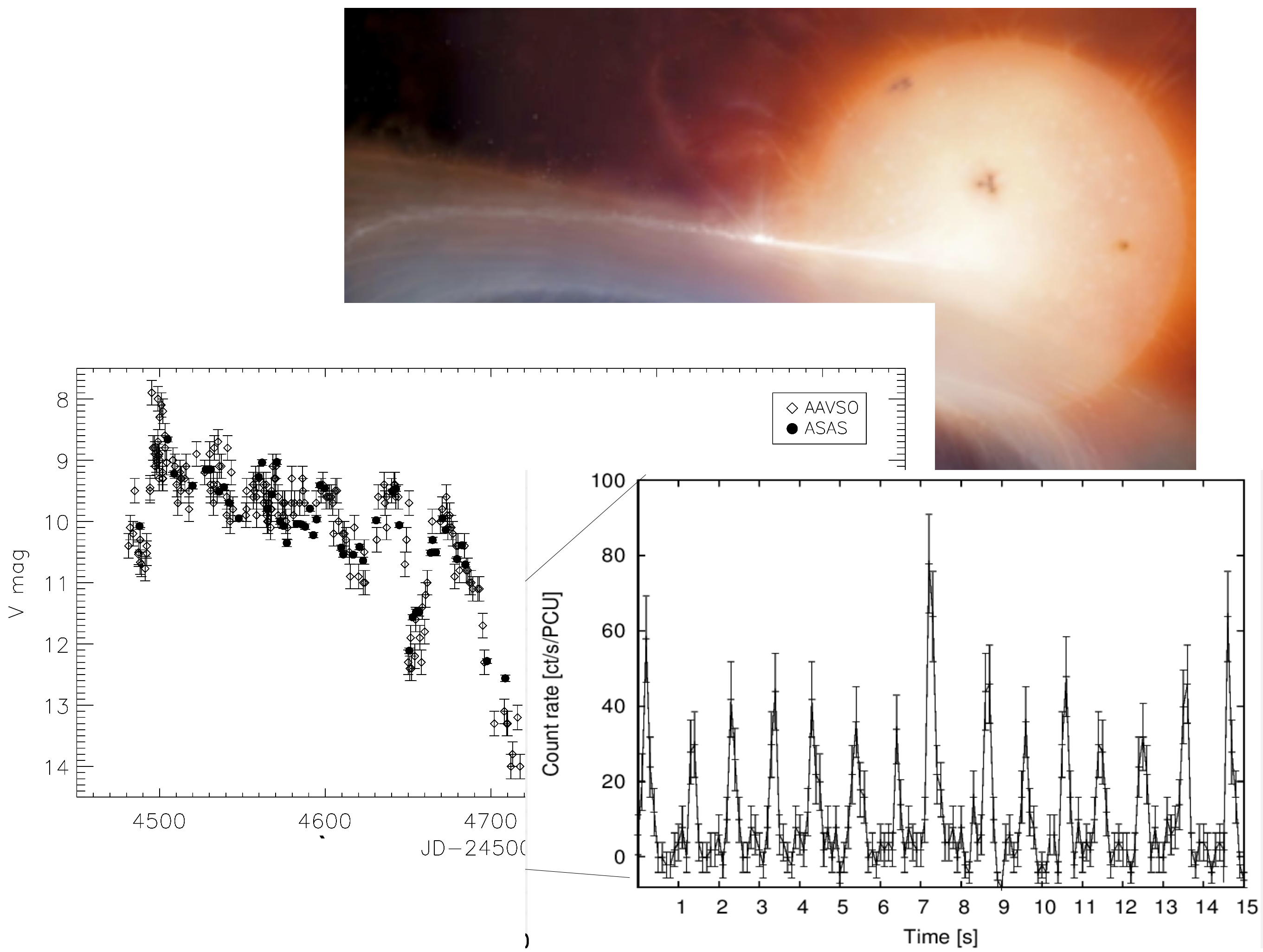


Coherent X-ray pulsations
(0.0025-100s) in accreting NS

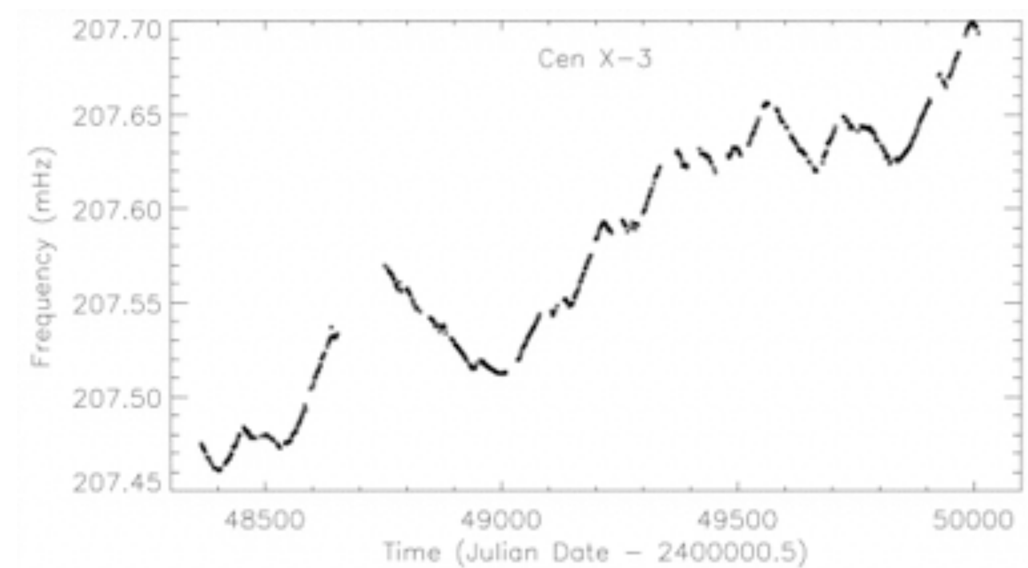


Rapid changes in spin rate

Strong stellar magnetic fields interacting with matter

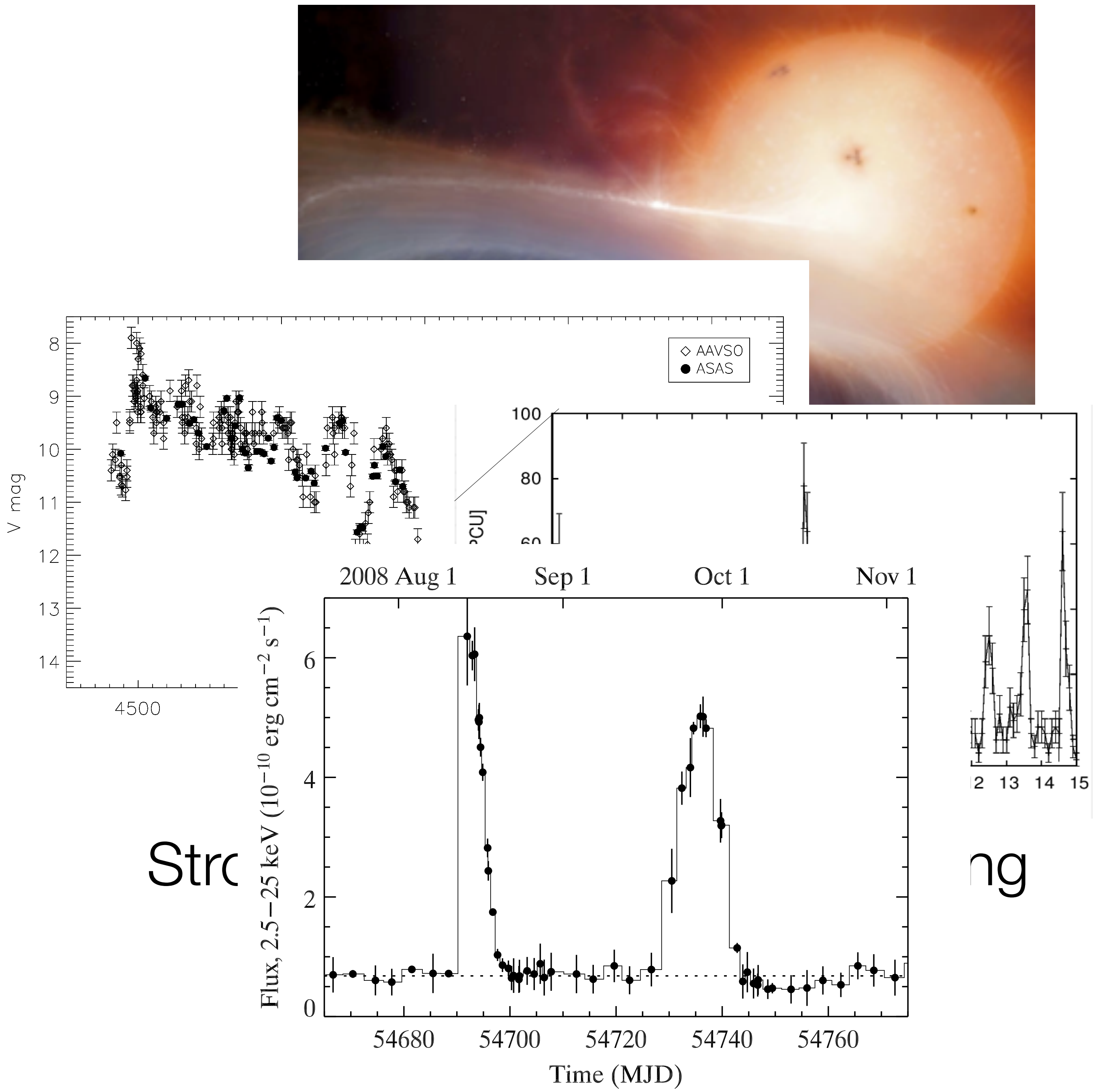


Strong rapid variability in accreting magnetic stars

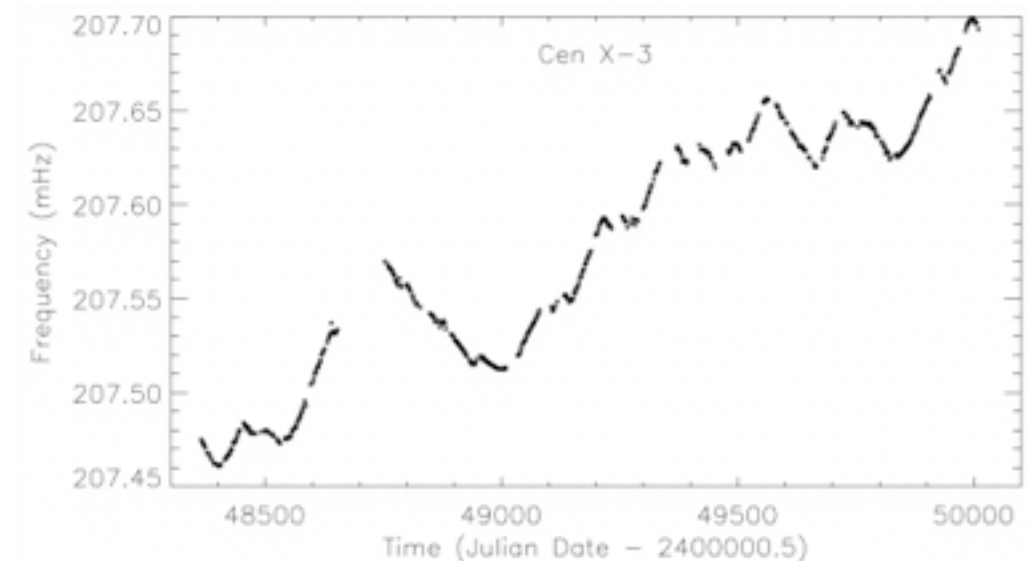


Rapid changes in spin rate

Strong stellar magnetic fields interacting with matter

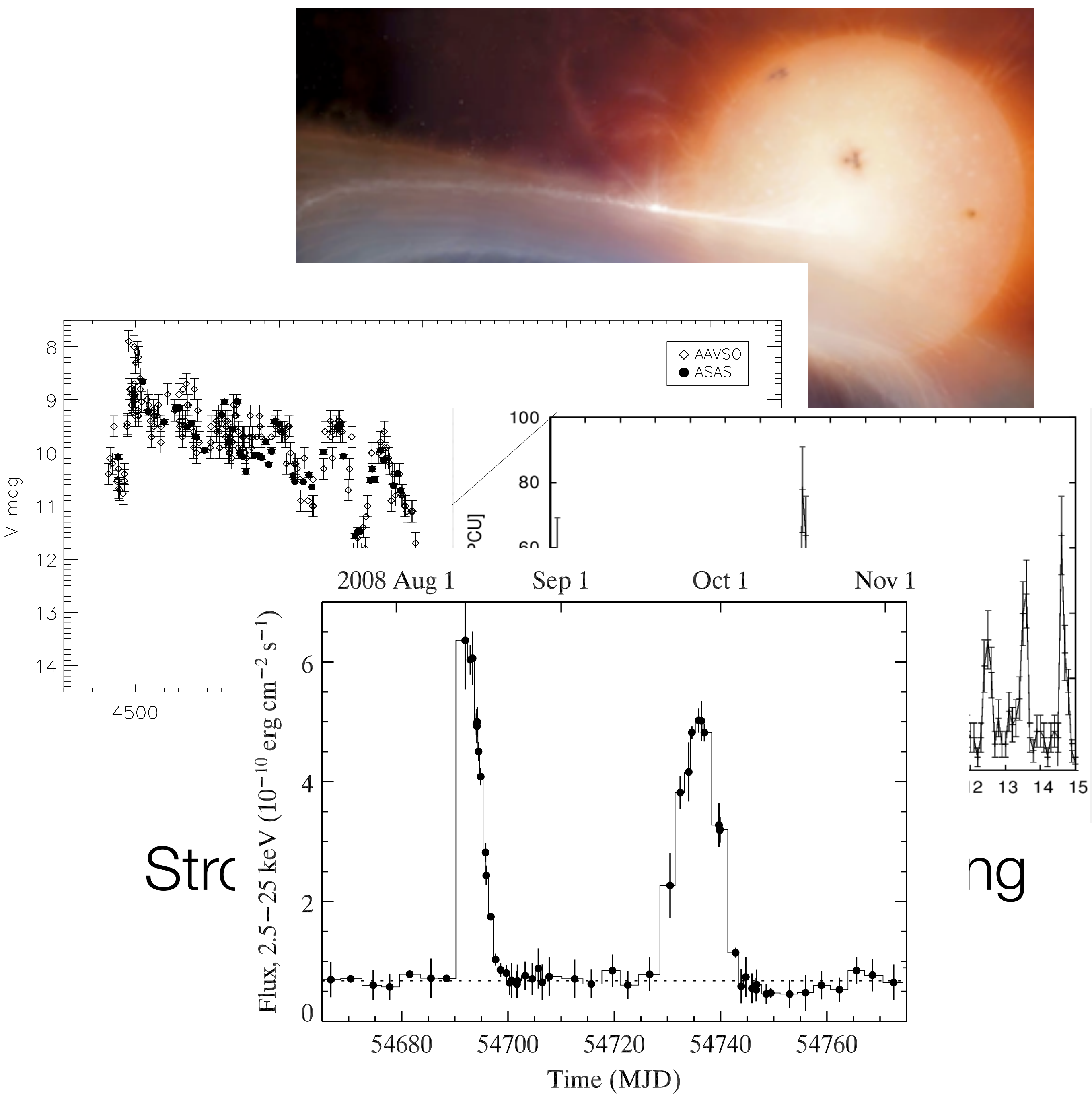


Unusual X-ray Outbursts (compared with black hole binaries)



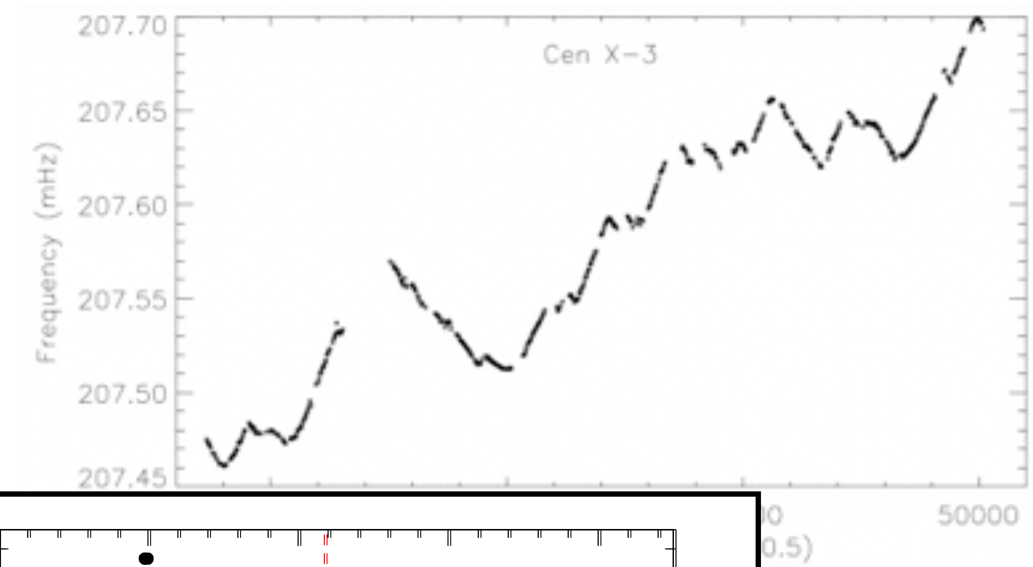
Rapid changes in spin rate

Strong stellar magnetic fields interacting with matter

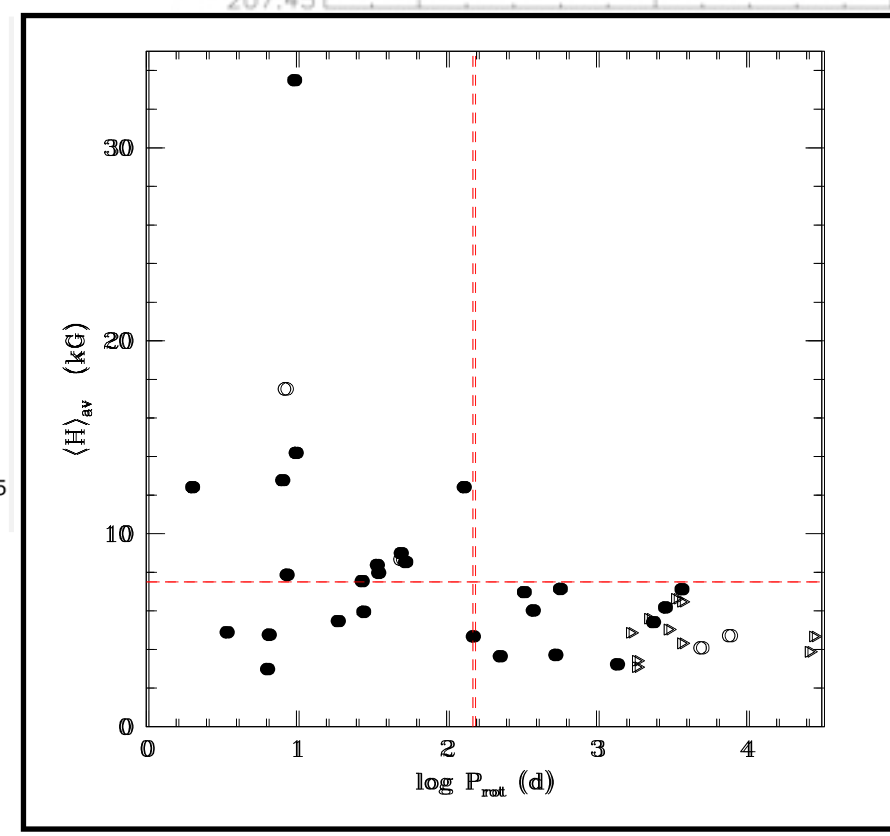


Stro ng

Unusual X-ray Outbursts (compared with black hole binaries)



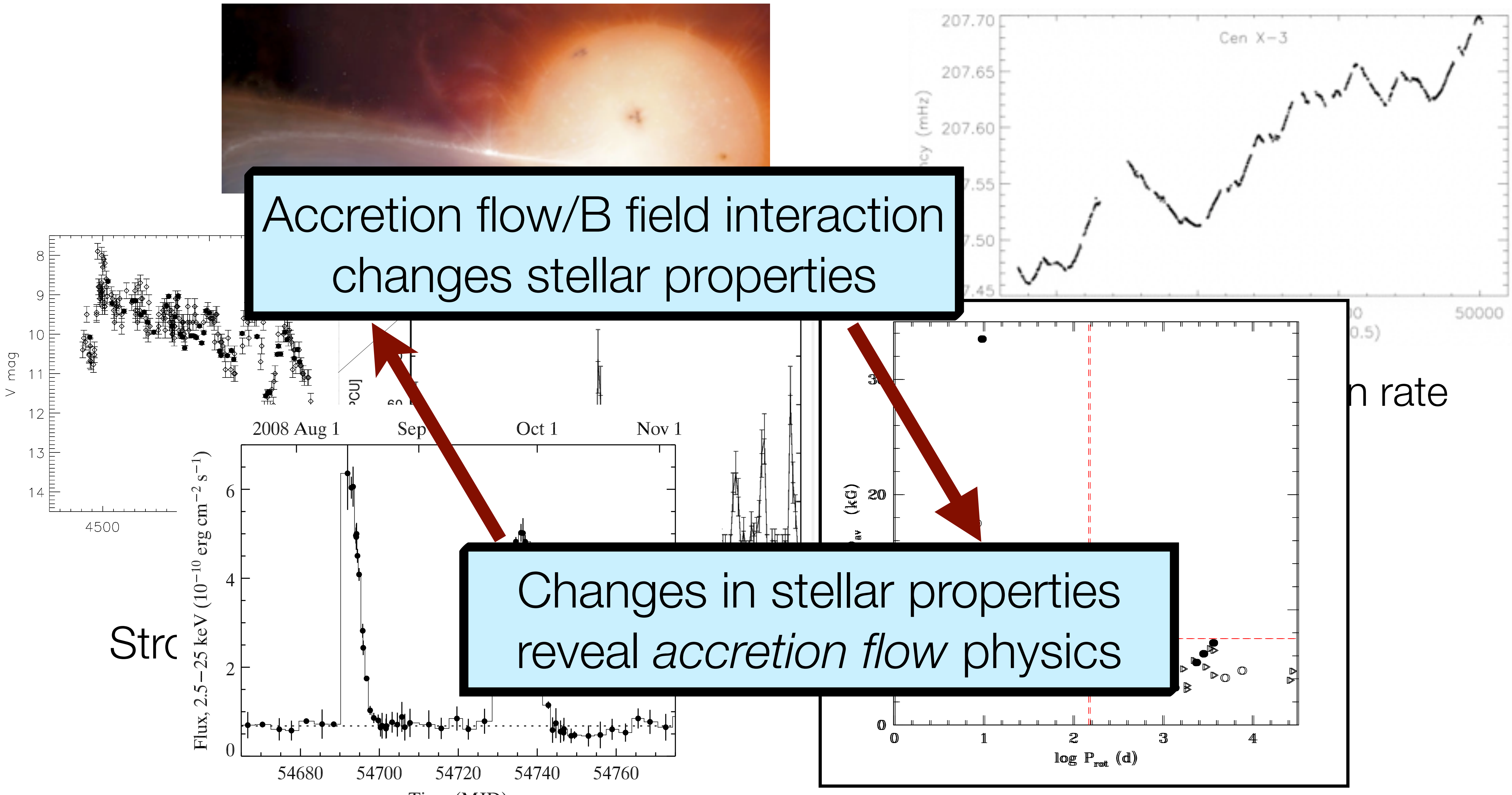
n rate



(Mathys 2008)

Long Rotation Periods

Strong stellar magnetic fields interacting with matter



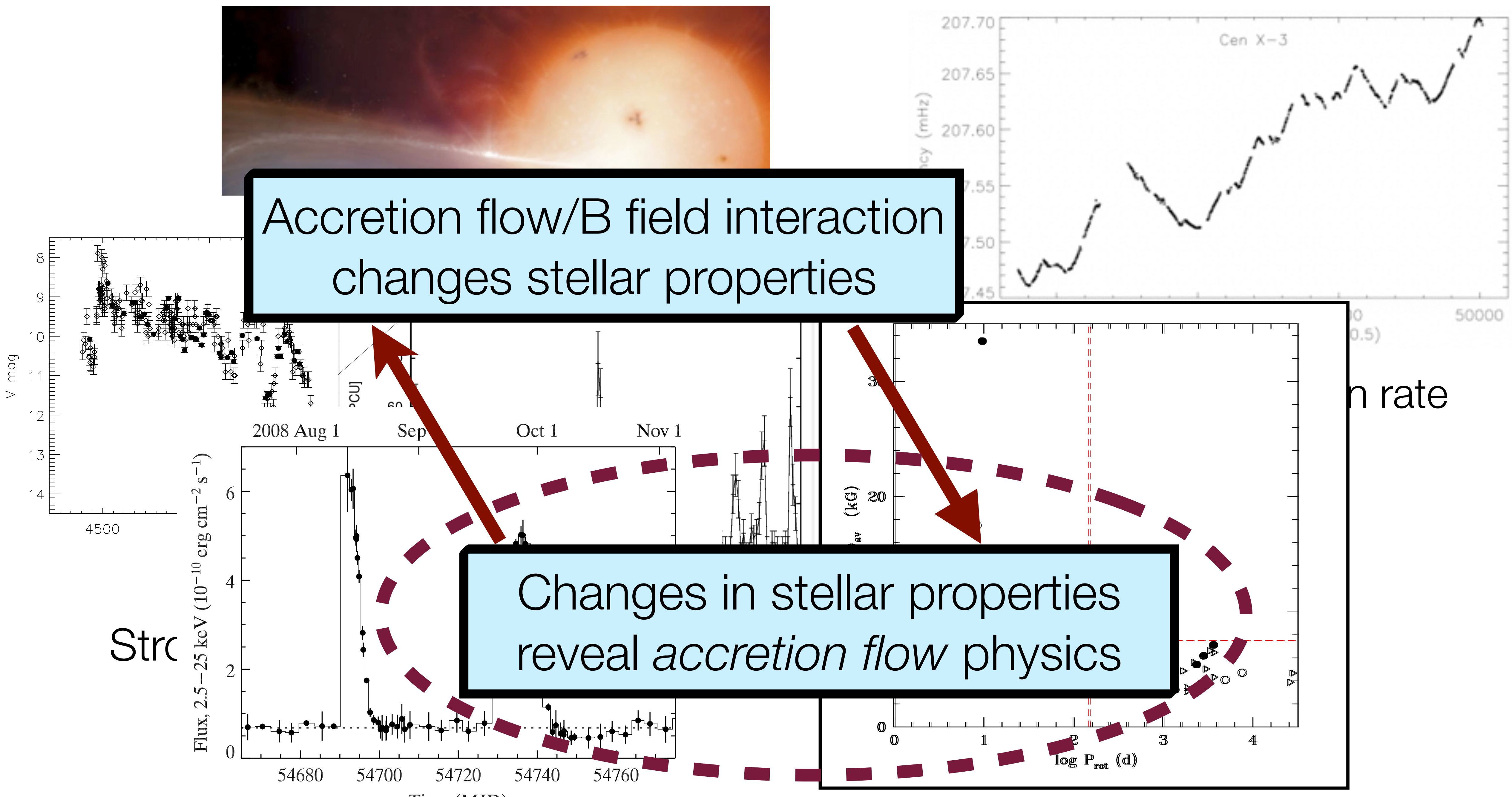
Accretion flow/B field interaction changes stellar properties

Changes in stellar properties reveal *accretion flow* physics

Unusual X-ray Outbursts (compared with black hole binaries)

Long Rotation Periods

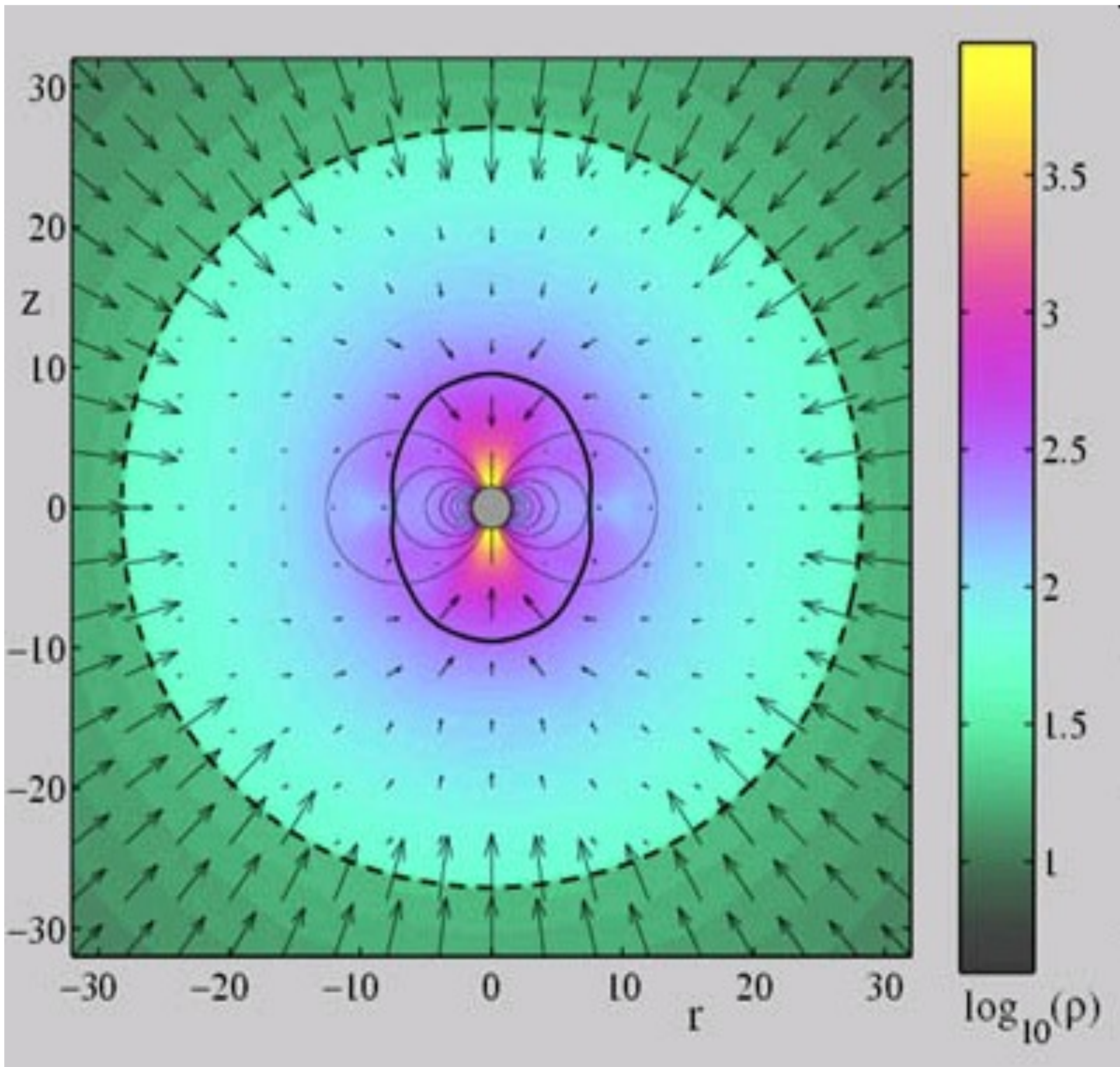
Strong stellar magnetic fields interacting with matter



Unusual X-ray Outbursts (compared with black hole binaries)

Long Rotation Periods

Channelled accretion onto strong B field



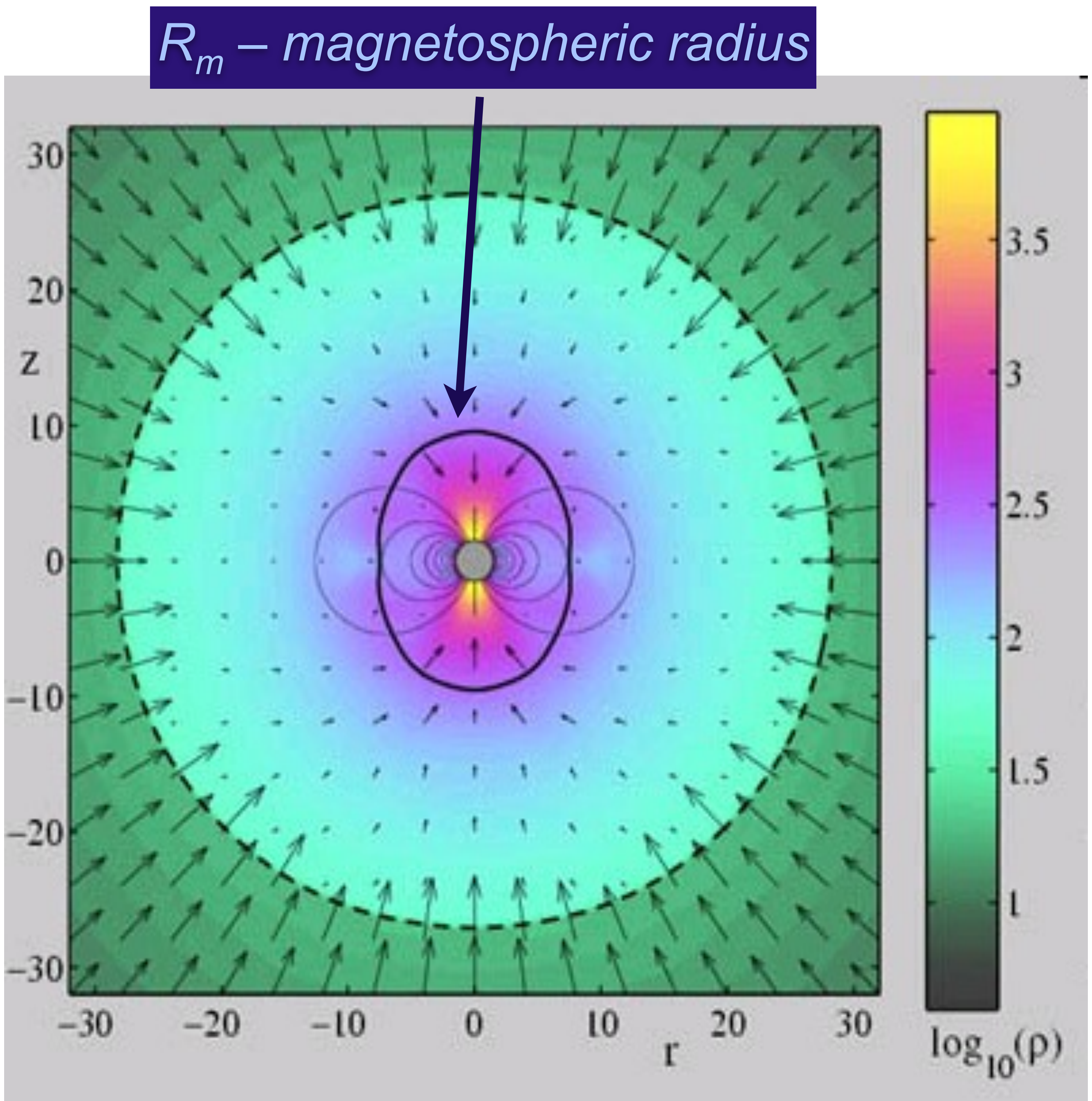
[Romanova et al. 2003]

Free-falling, spherically-symmetric gas:

B controls gas dynamics when $P_{mag} \sim P_{free\ fall}$:

$$\frac{B^2}{8\pi} = \rho v_{ff}^2$$

Channelled accretion onto strong B field



[Romanova et al. 2003]

Free-falling, spherically-symmetric gas:
B controls gas dynamics when $P_{mag} \sim P_{free\ fall}$:

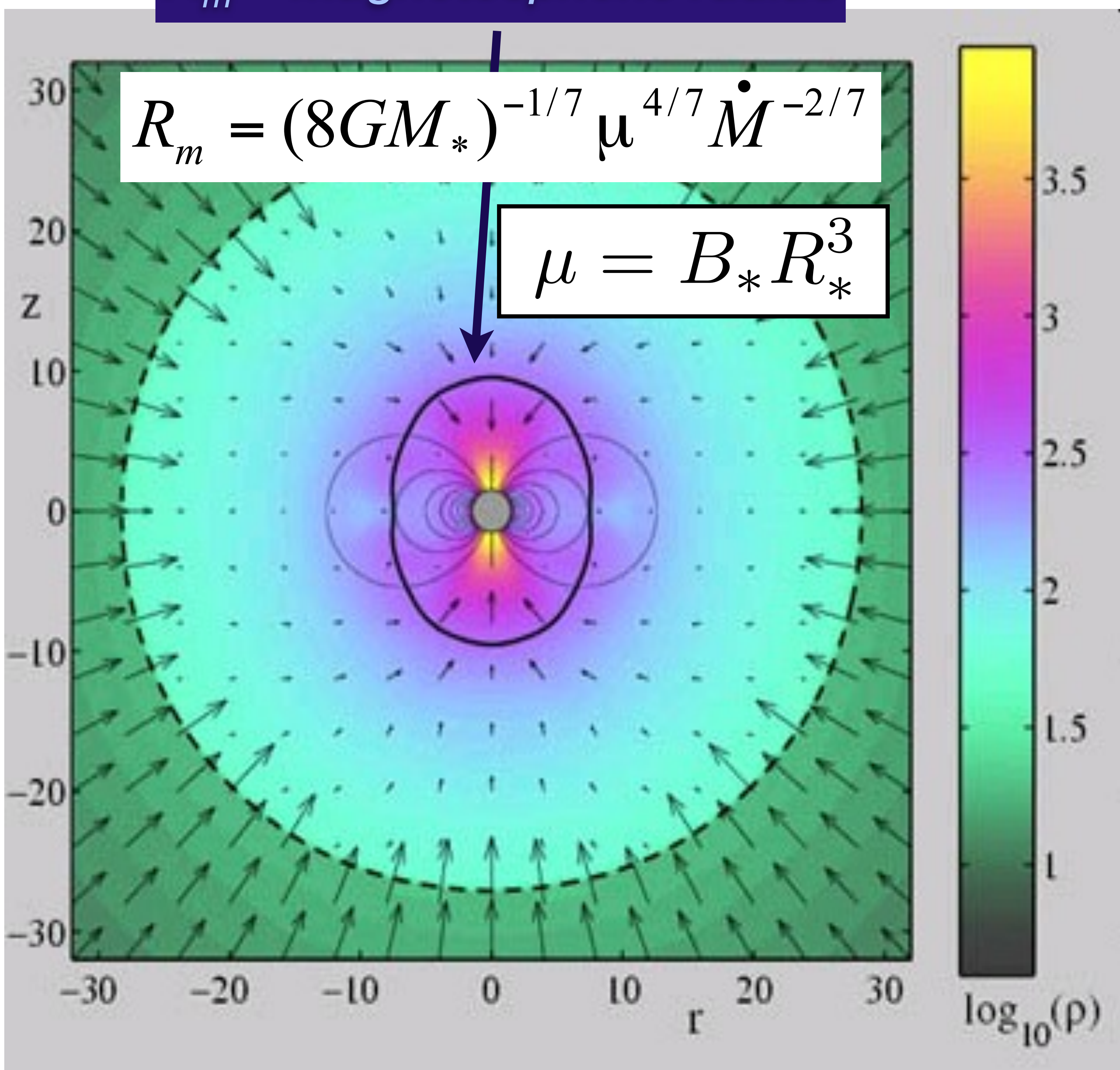
$$\frac{B^2}{8\pi} = \rho v_{ff}^2$$

Channelled accretion onto strong B field

R_m – magnetospheric radius

$$R_m = (8GM_*)^{-1/7}\mu^{4/7}\dot{M}^{-2/7}$$

$$\mu = B_* R_*^3$$



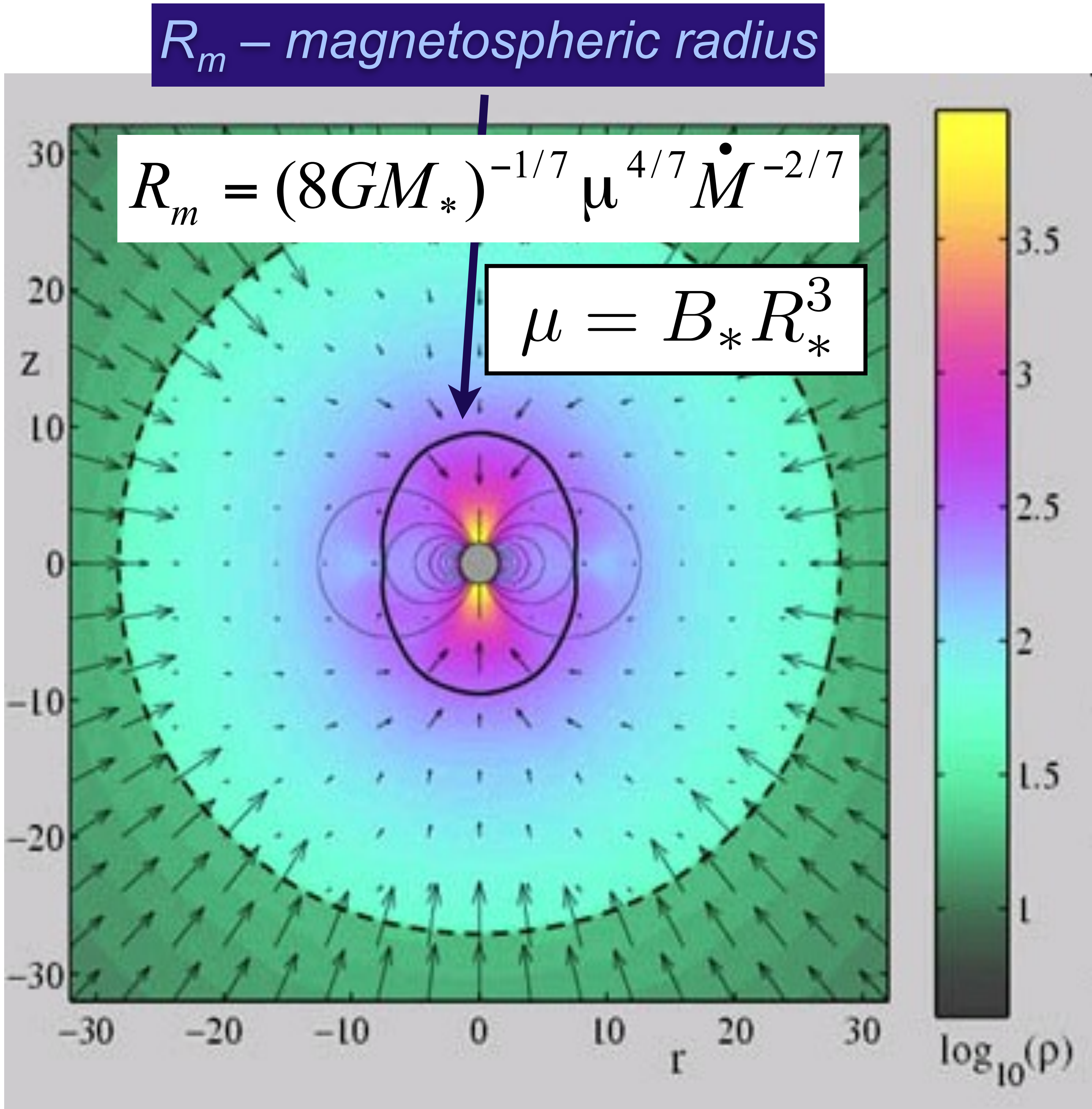
[Romanova et al. 2003]

Free-falling, spherically-symmetric gas:

B controls gas dynamics when $P_{mag} \sim P_{free\ fall}$:

$$\frac{B^2}{8\pi} = \rho v_{ff}^2$$

Channelled accretion onto strong B field

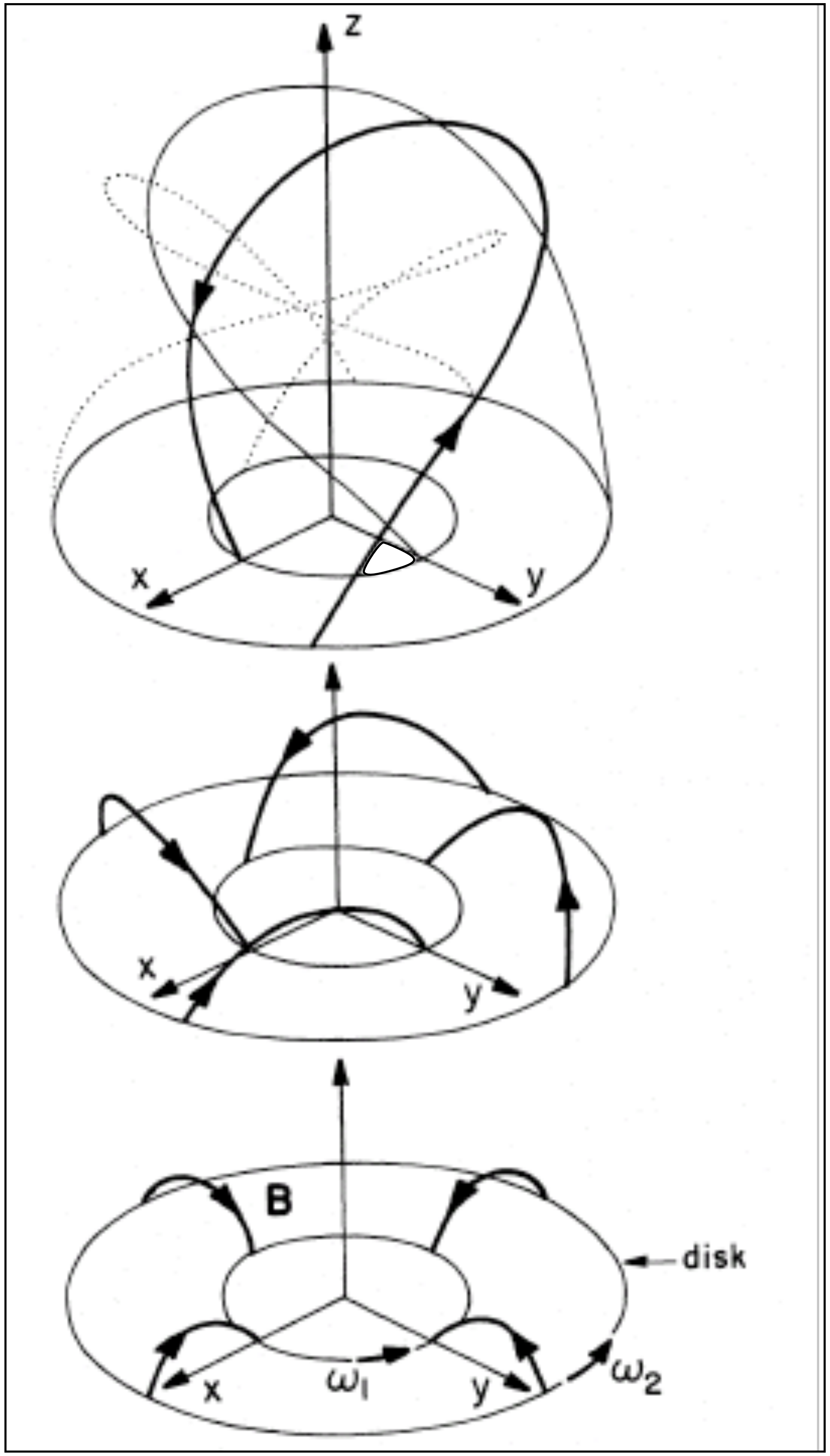


[Romanova et al. 2003]

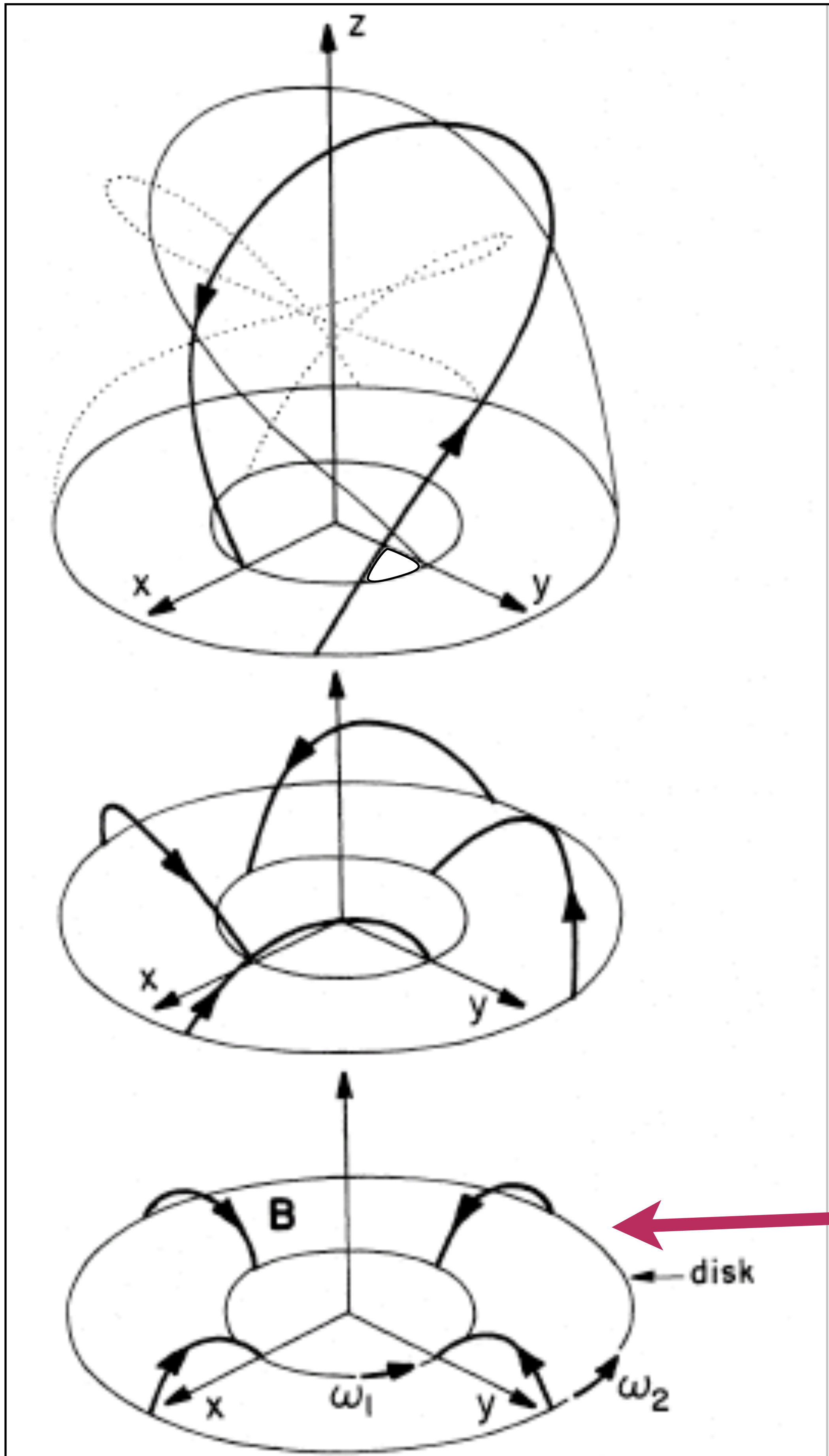
Free-falling, spherically-symmetric gas:
B controls gas dynamics when $P_{mag} \sim P_{free\ fall}$:

$$\frac{B^2}{8\pi} = \rho v_{ff}^2$$

BUT: differential rotation between star and disc

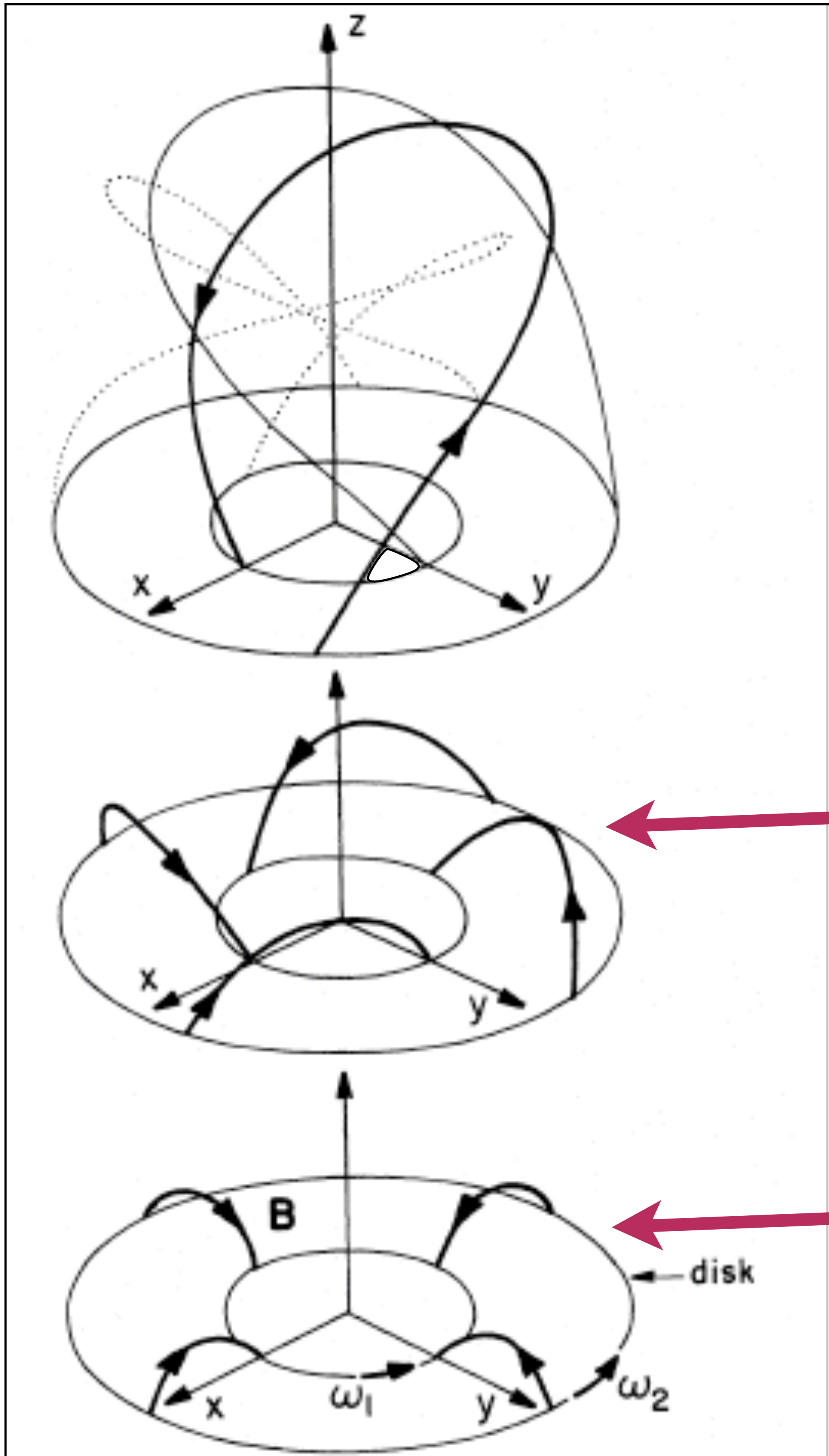


[Lovelace et al.,1995]



[Lovelace et al.,1995]

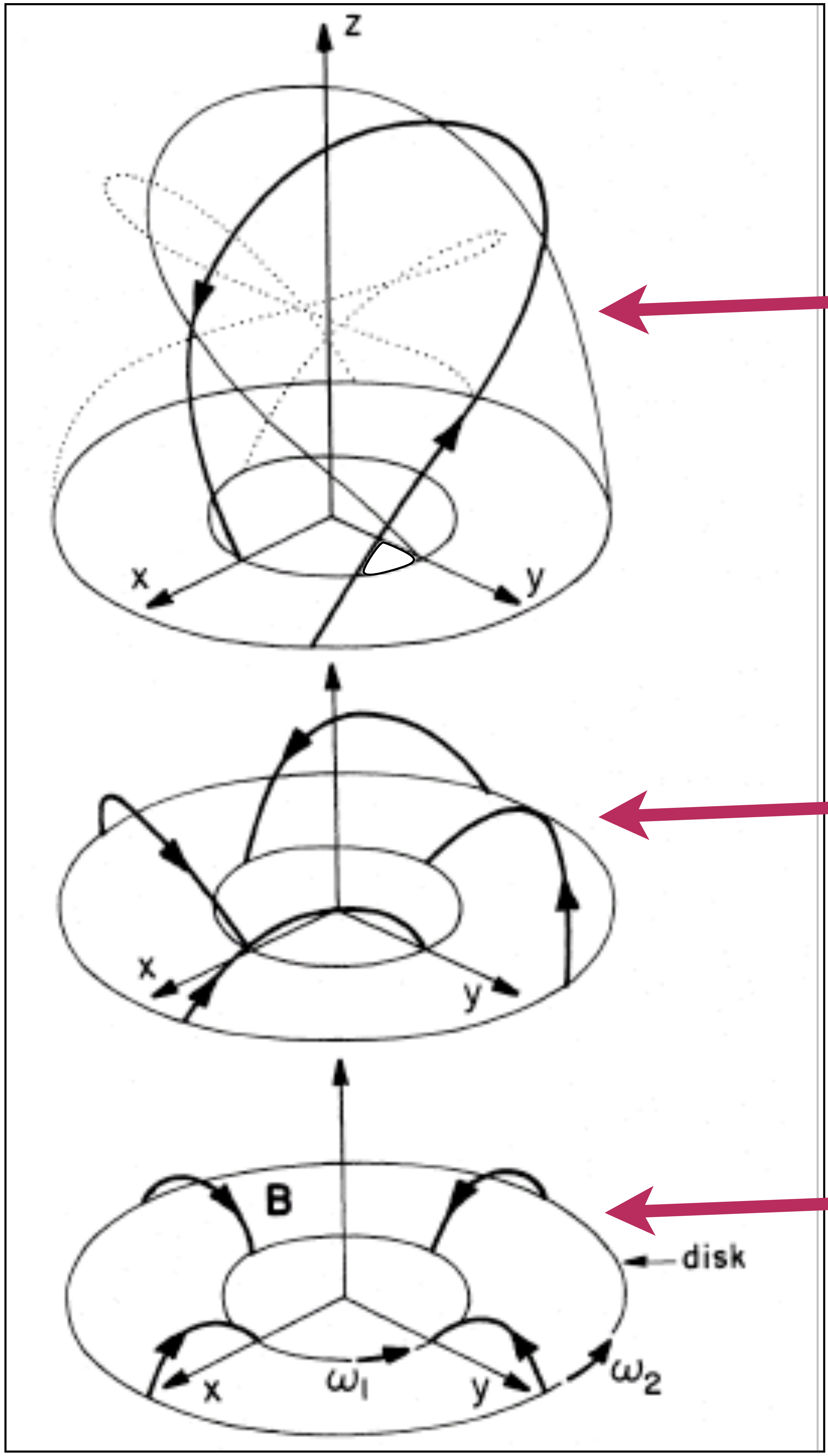
Field lines anchor in ionized disc



[Lovelace et al.,1995]

Differential rotation shears field

Field lines anchor in ionized disc

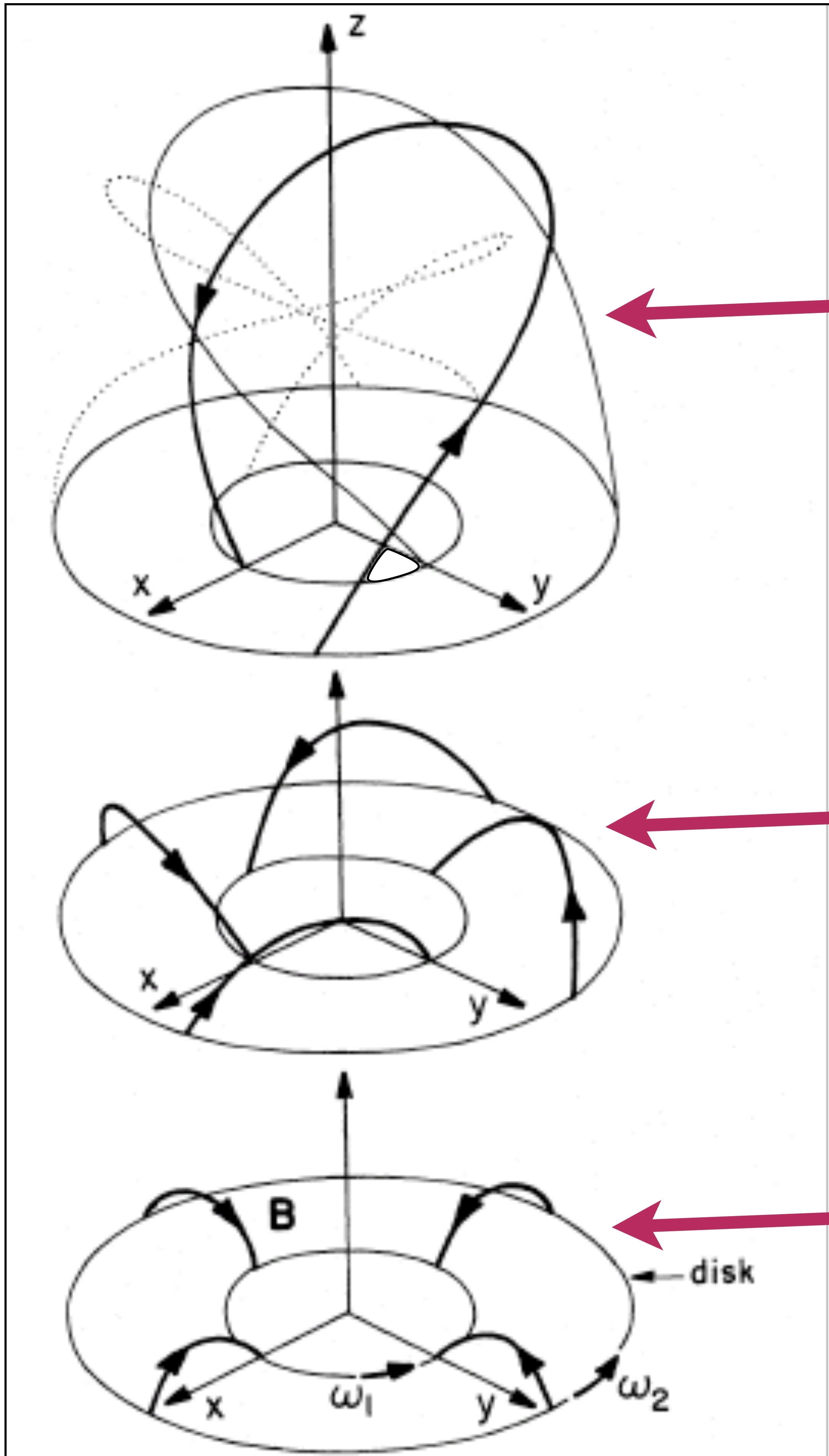


[Lovelace et al.,1995]

Field lines **inflate** and **open**, severing connection to star

Differential rotation shears field

Field lines anchor in ionized disc



[Lovelace et al.,1995]

Field lines **inflate** and **open**, severing connection to star

$$\tau = \frac{\eta \mu^2 \Delta r}{r^4}$$

Torque on Star

D … shears field

Fiel
disc

$$\eta = \frac{B_\phi}{B_p} < 1$$

generated toroidal field

$$\frac{\Delta r}{r} < 1$$

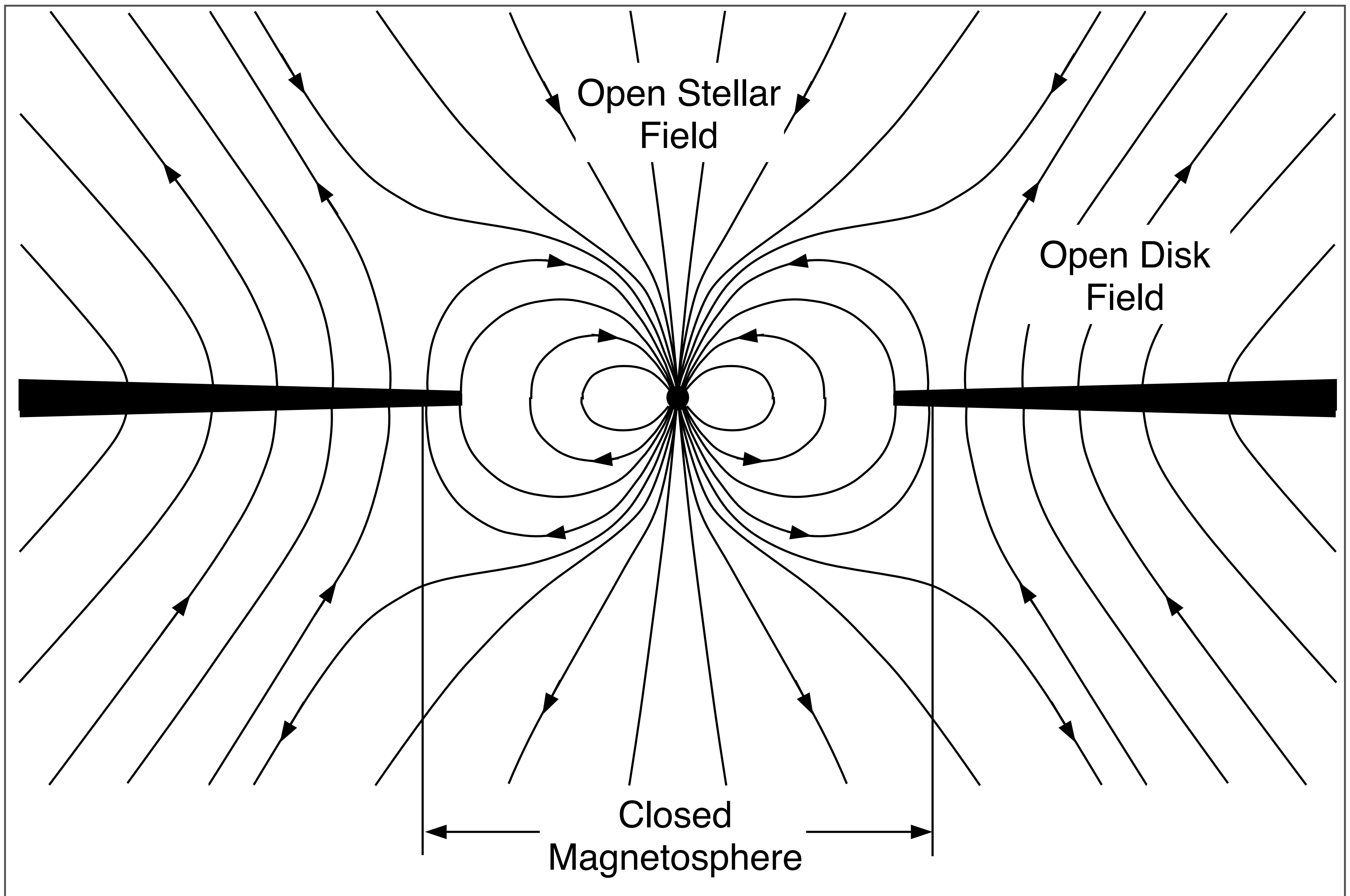
coupled region

Global Field Topology

$$R_m = (8GM_*)^{-1/7} \mu^{4/7} \dot{M}^{-2/7}$$ →

Global Field Topology

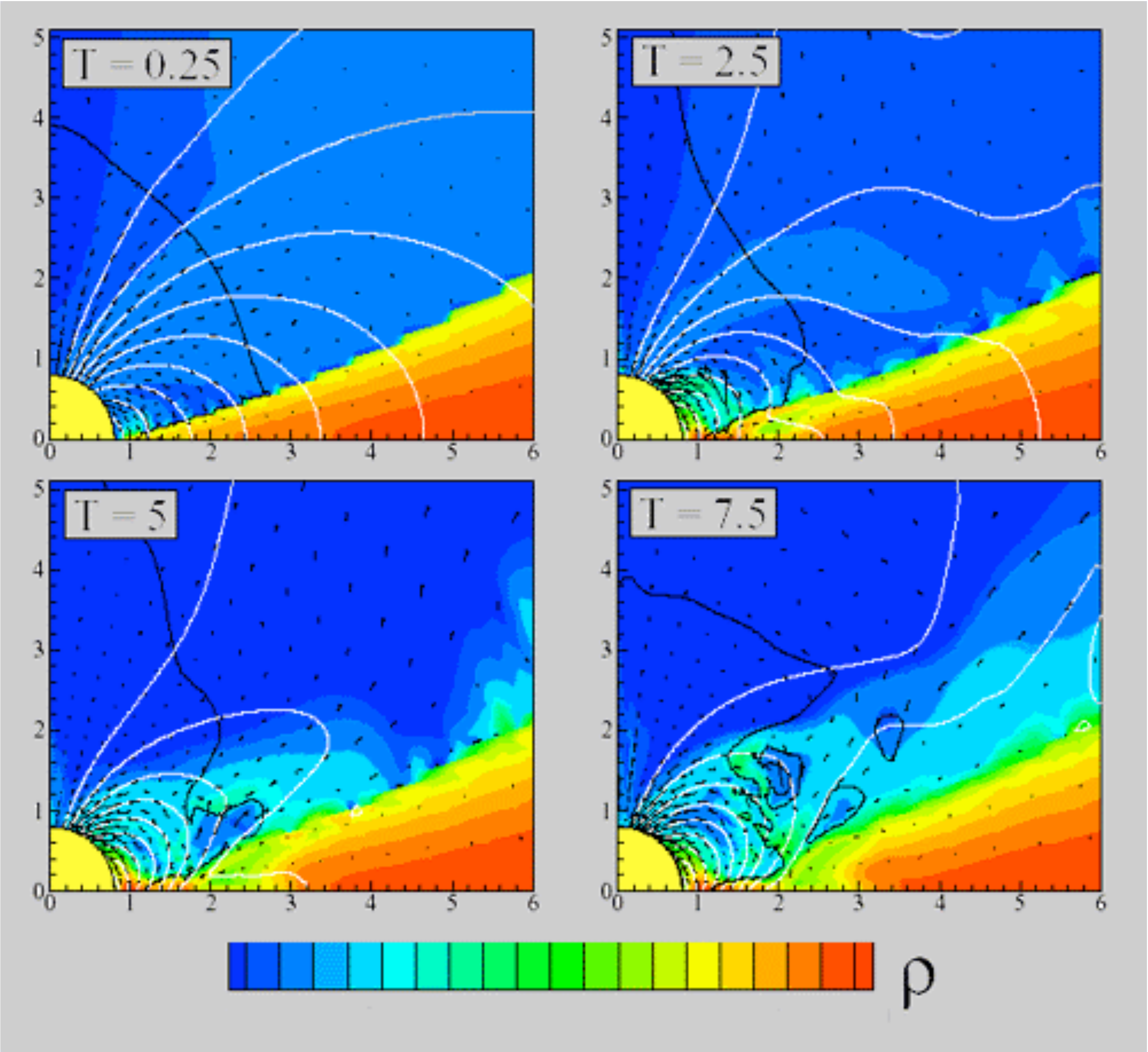
$$R_m = (8GM_*)^{-1/7}\mu^{4/7}\dot{M}^{-2/7} \rightarrow R_m = \eta^{1/5}(16GM_*)^{-1/10}r_c^{3/10}\mu^{2/5}\dot{M}^{-1/5}$$



[Lovelace et al. 1995]

$$r_c = \left(\frac{GM_*}{\Omega_*^2}\right)^{1/3}$$

R_m depends on **Co-rotation radius:** Keplerian disc rotation = stellar spin



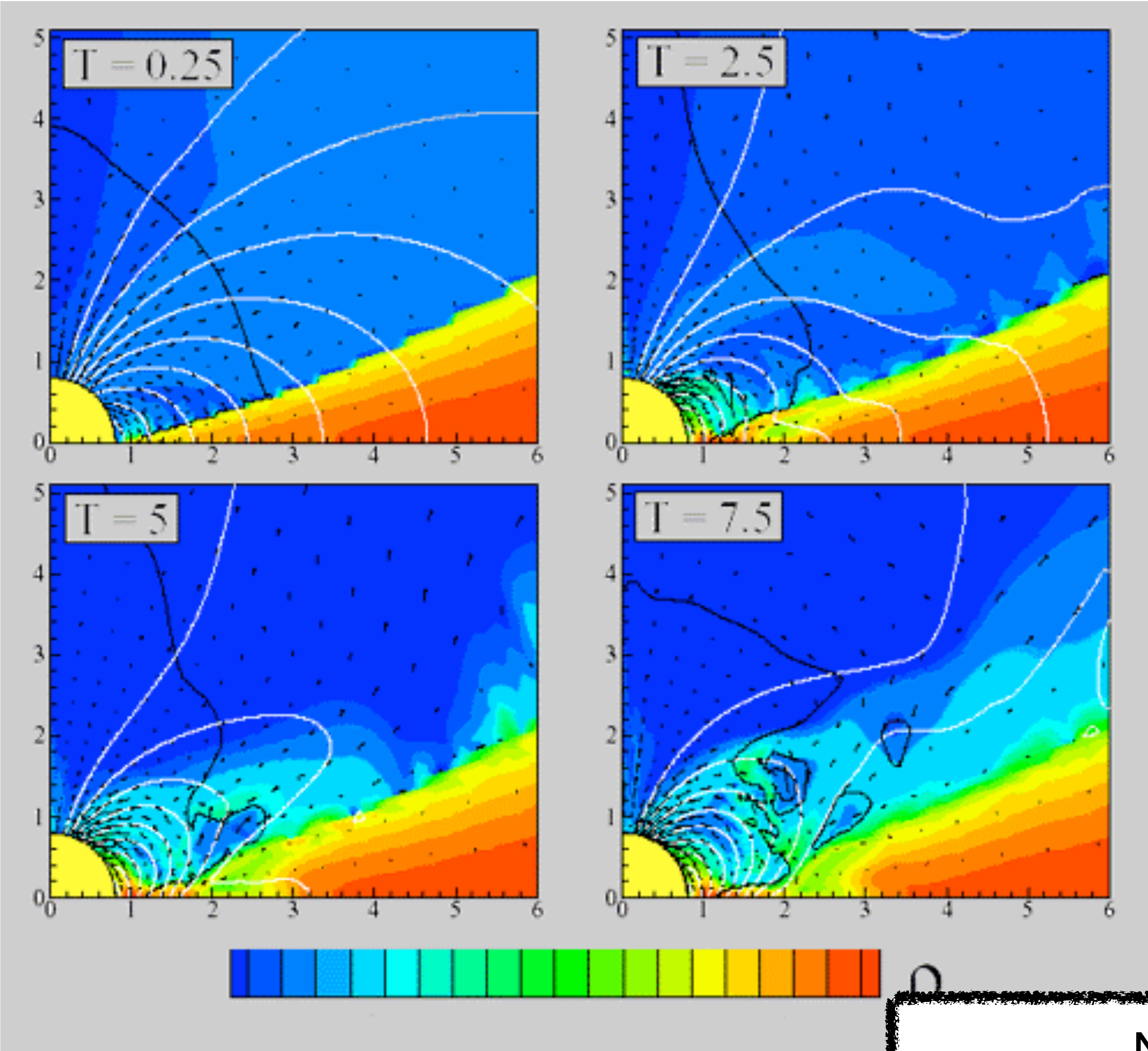
Romanova et al. 2009

e.g. Miller & Stone 1997, Hayashi et al. 1996, Goodson et al. 1997, Romanova, Lovelace, Ustyugova, Lii et al. 2002-2013, Zanni & Ferreira 2013

Dynamic picture of accretion/outflow supported by simulations

Uncertainties:

- How much field reconnects?
- How quickly can field diffuse through disc?
- How is an outflow launched? how much material is expelled?



Roma

e.g. Miller & Stone 1997, Hayashi et al. 1996, Goodson et al. 1997, Romanova, Lovelace, Ustyugova, Lii et al. 2002-2013, Zanni & Ferreira 2013

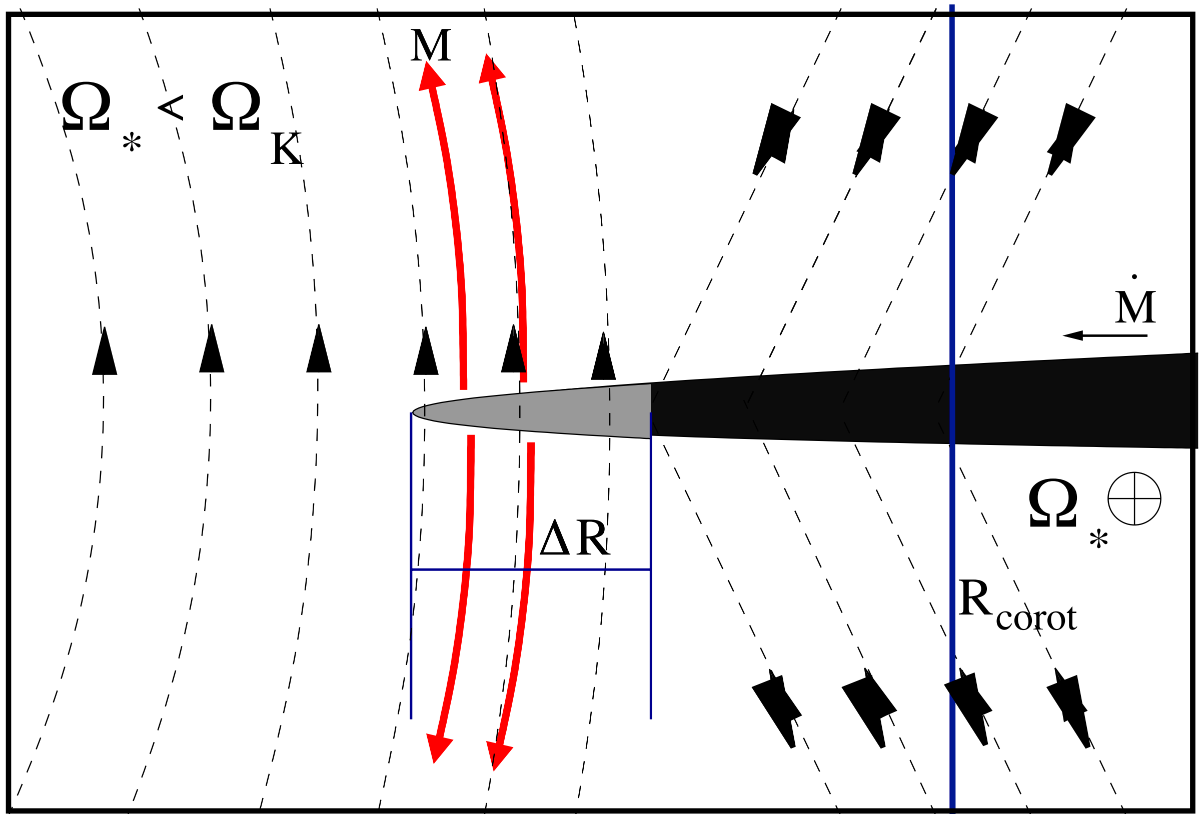
Dynamic picture of accretion/outflow supported by simulations

Uncertainties:

- How much field reconnects?
- How quickly can field diffuse through disc?
- How is an outflow launched? how much material is expelled?

Need **FULL MHD SIMULATIONS** to answer these questions: stellar B field interacts with MRI in disk: these now possible (Romanova et al. 2012)

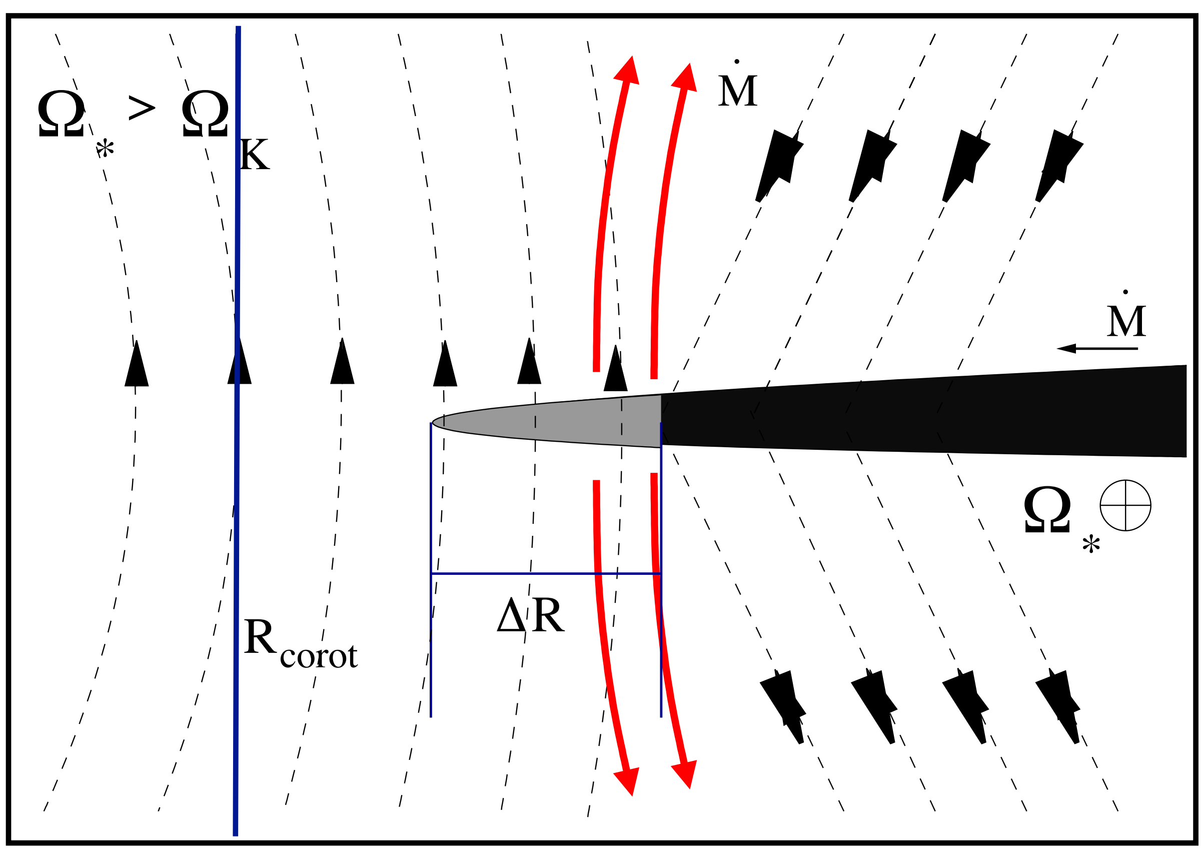
Two Disc States



e.g. Pringle & Rees (1972)

$R_m < R_{corot}$:

- Angular momentum is *extracted* from the disc
- Accretion onto star
- Spin-up

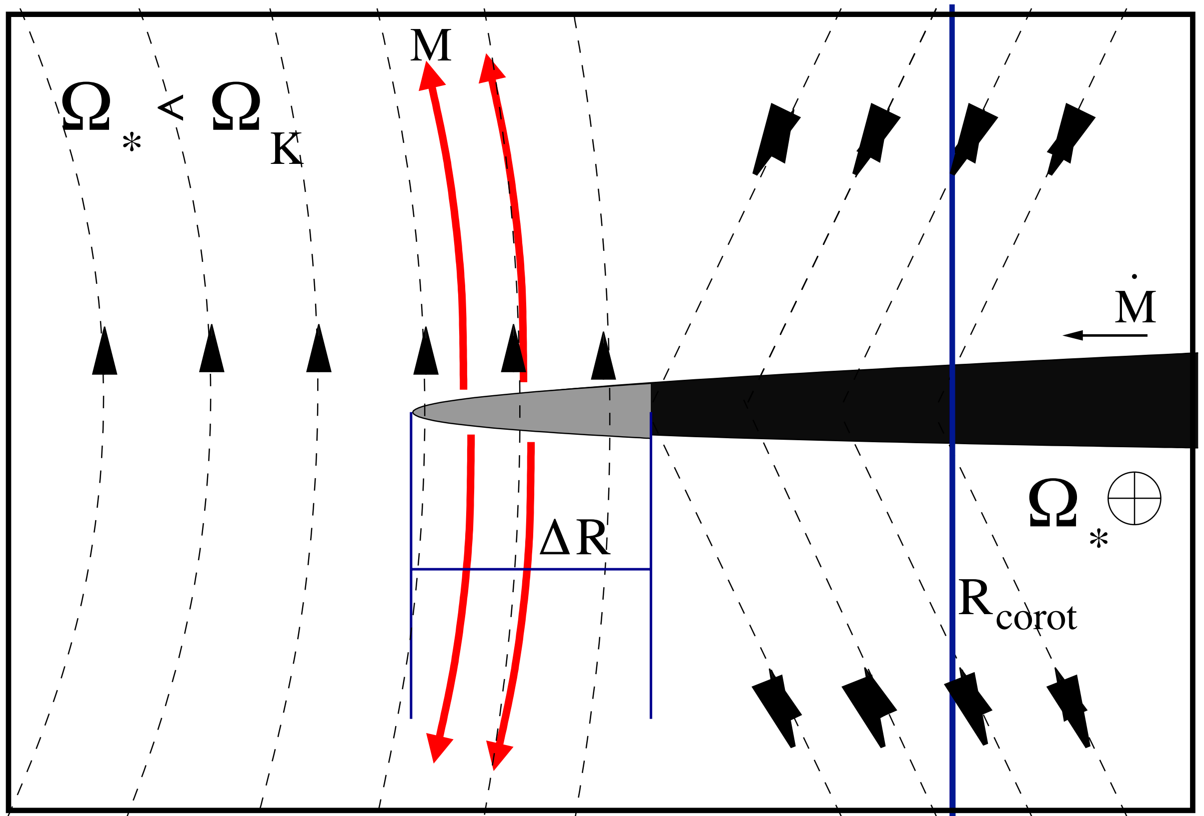


Illarionov & Sunyaev (1975)

$R_m > R_{corot}$:

- Angular momentum is *added* to the disc
- Spin-down of the star
- Expelled outflow (?)

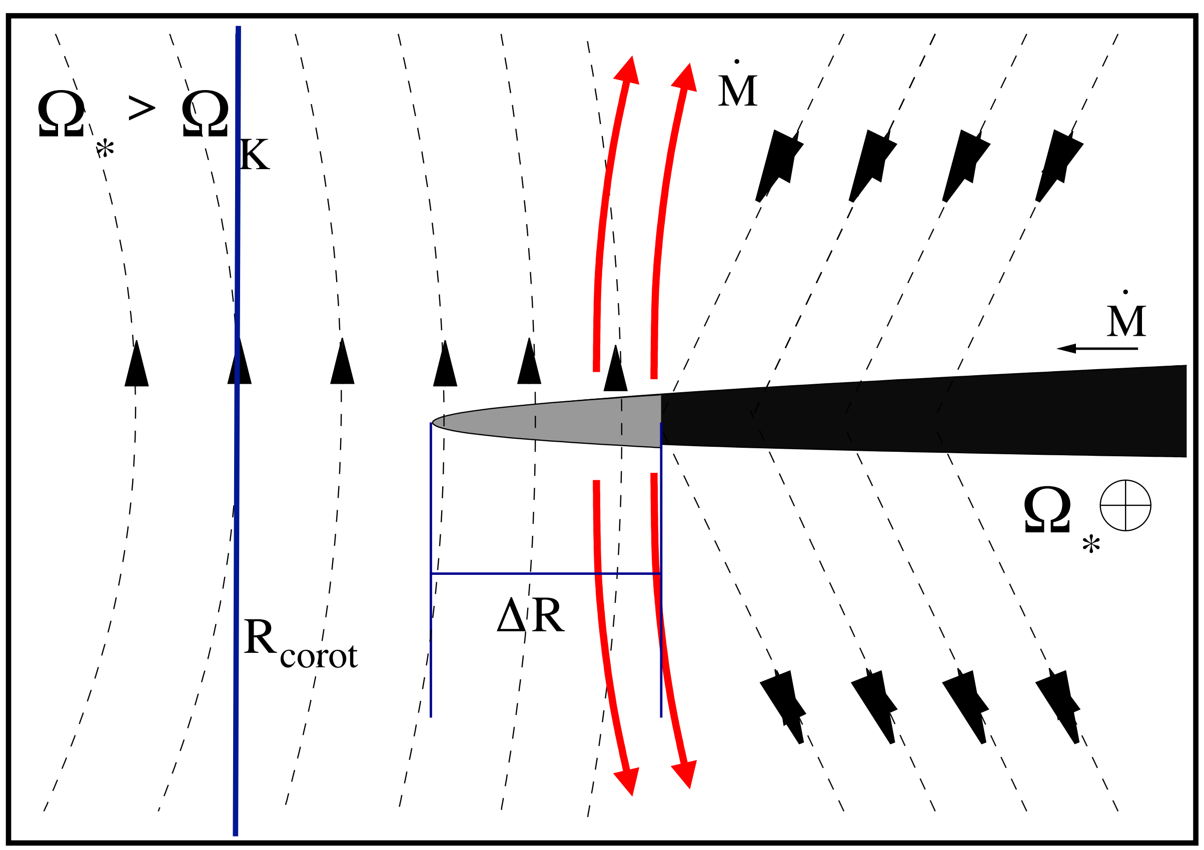
Two Disc States



e.g. Pringle & Rees (1972)

R_m < R_{corot}:

- Angular momentum is *extracted* from the disc
- Accretion onto star
- Spin-up



Illarionov & Sunyaev (1975)

R_m > R_{corot}:

- Angular momentum is *added* to the disc
- Spin-down of the star
- Expelled outflow (?)

"Propeller"

$$R_m = (8GM_*)^{-1/7}\mu^{4/7}\dot{M}^{-2/7}$$

Centrifugal barrier to accretion

$R_m > R_{corot}$: star spins faster than disc – ‘propeller’

Illarianov & Sunyaev
(1975)

Centrifugal barrier to accretion

$R_m > R_{corot}$: star spins faster than disc – ‘propeller’

vs.

Illarianov & Sunyaev
(1975)

Centrifugal barrier to accretion

$R_m > R_{corot}$: star spins faster than disc – 'propeller'

Illarianov & Sunyaev (1975)

vs.

Spruit & Taam (1993); D'Angelo & Spruit (2010)

Centrifugal barrier to accretion

$R_m > R_{corot}$: star spins faster than disc – 'propeller'

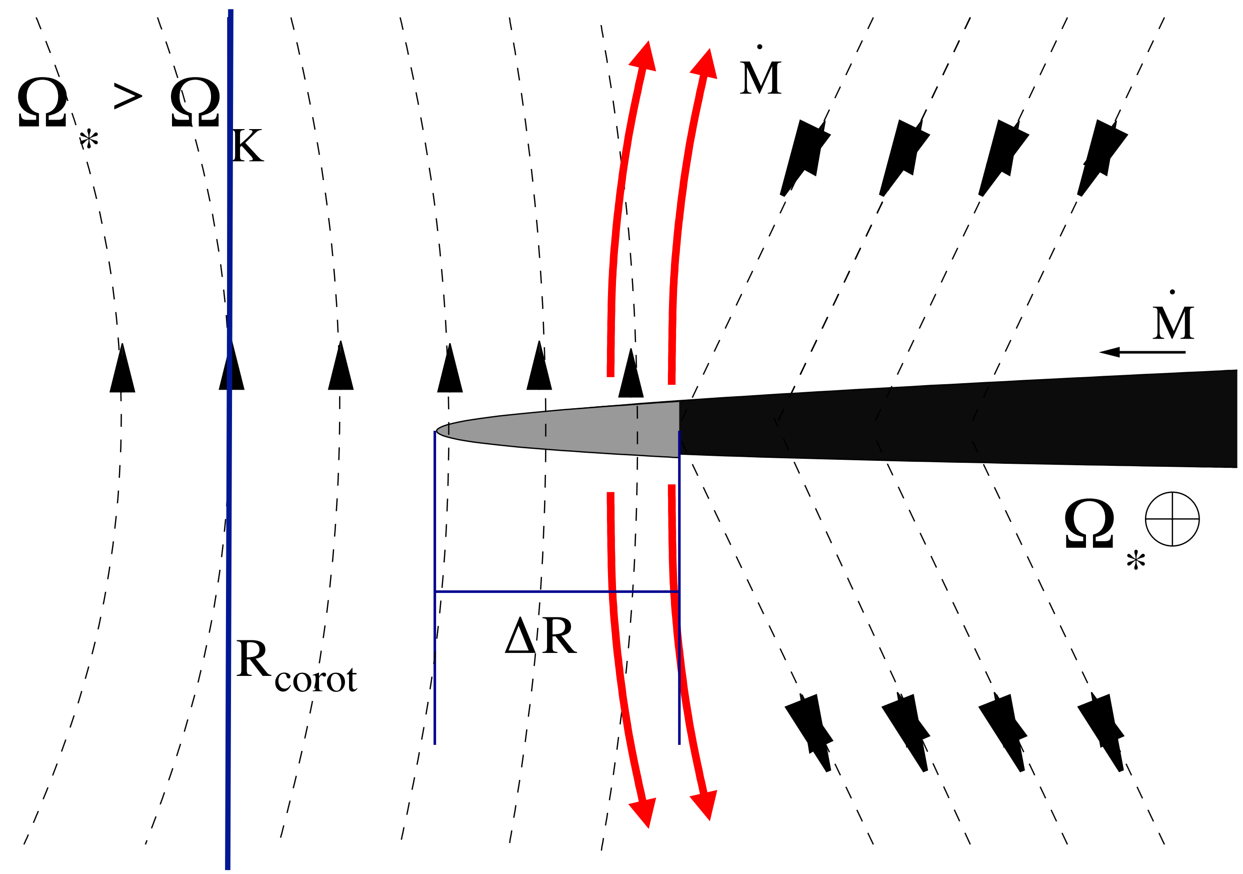
Illarianov & Sunyaev (1975)

vs.

Spruit & Taam (1993); D'Angelo & Spruit (2010)

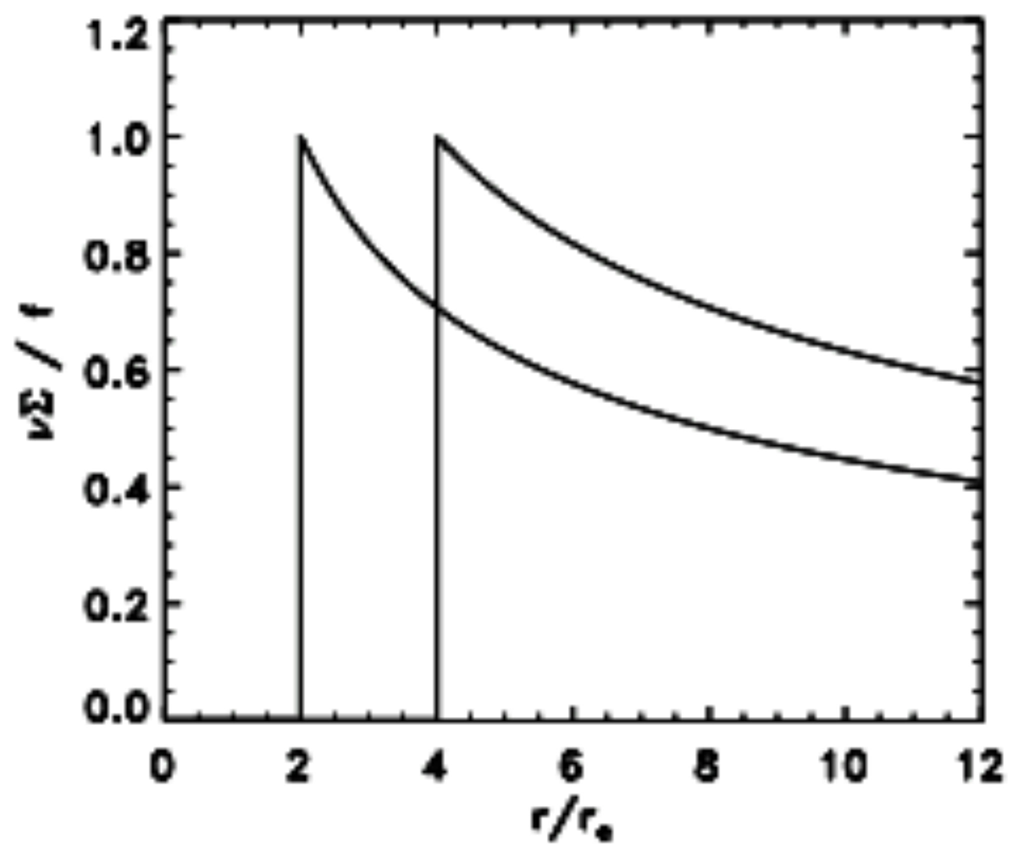
Most gas is not necessarily expelled!

Accretion discs without accretion



If relative velocity between disc and star is not large (r_m<1.3 r_c): *not enough* energy to expel gas

P_K ~ P_{spin}



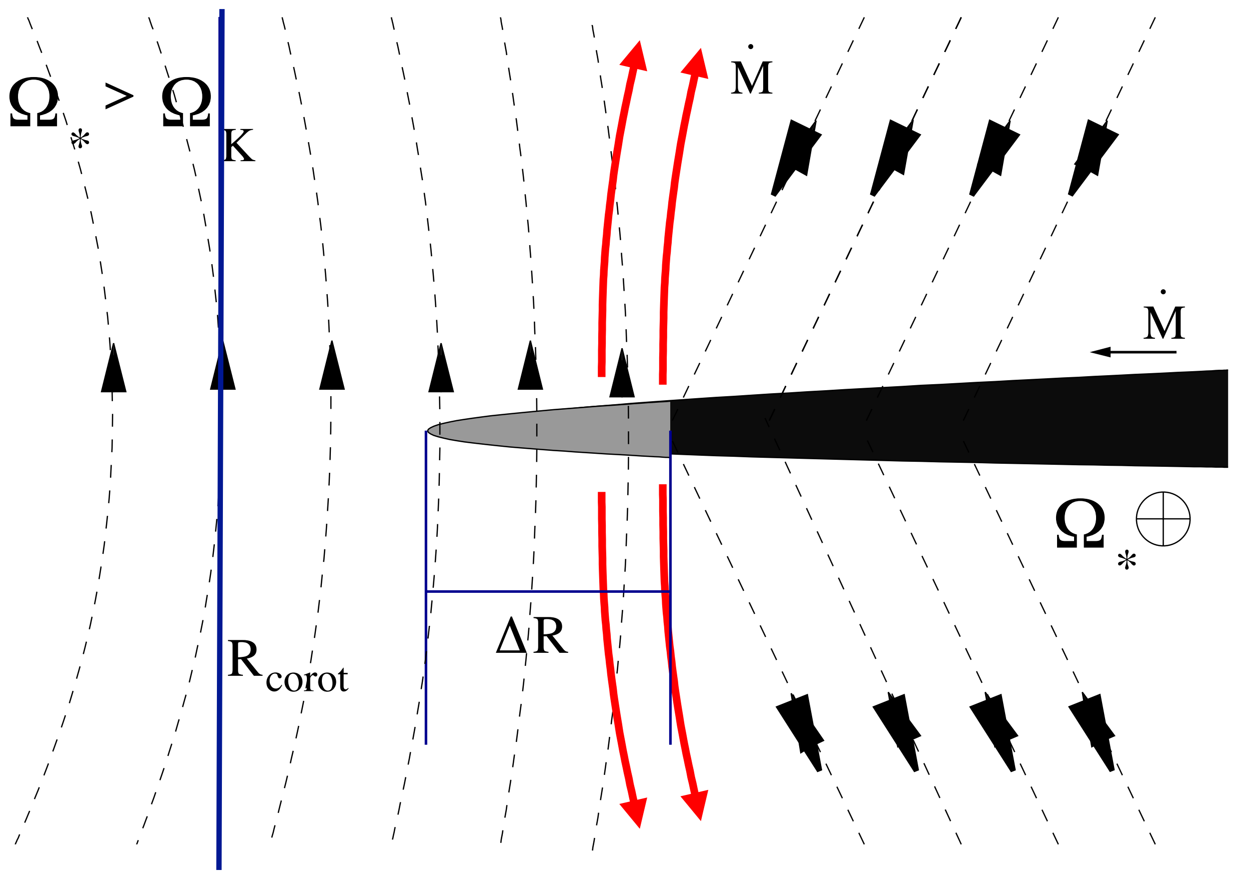
Dead disc: angular momentum added by disc-field interaction carried out through disc (Sunyaev & Shakura, 1977)

Mass is stored in disc around R_m

Episodic Accretion Bursts

Centrifugal barrier piles up gas near R_{corot}...

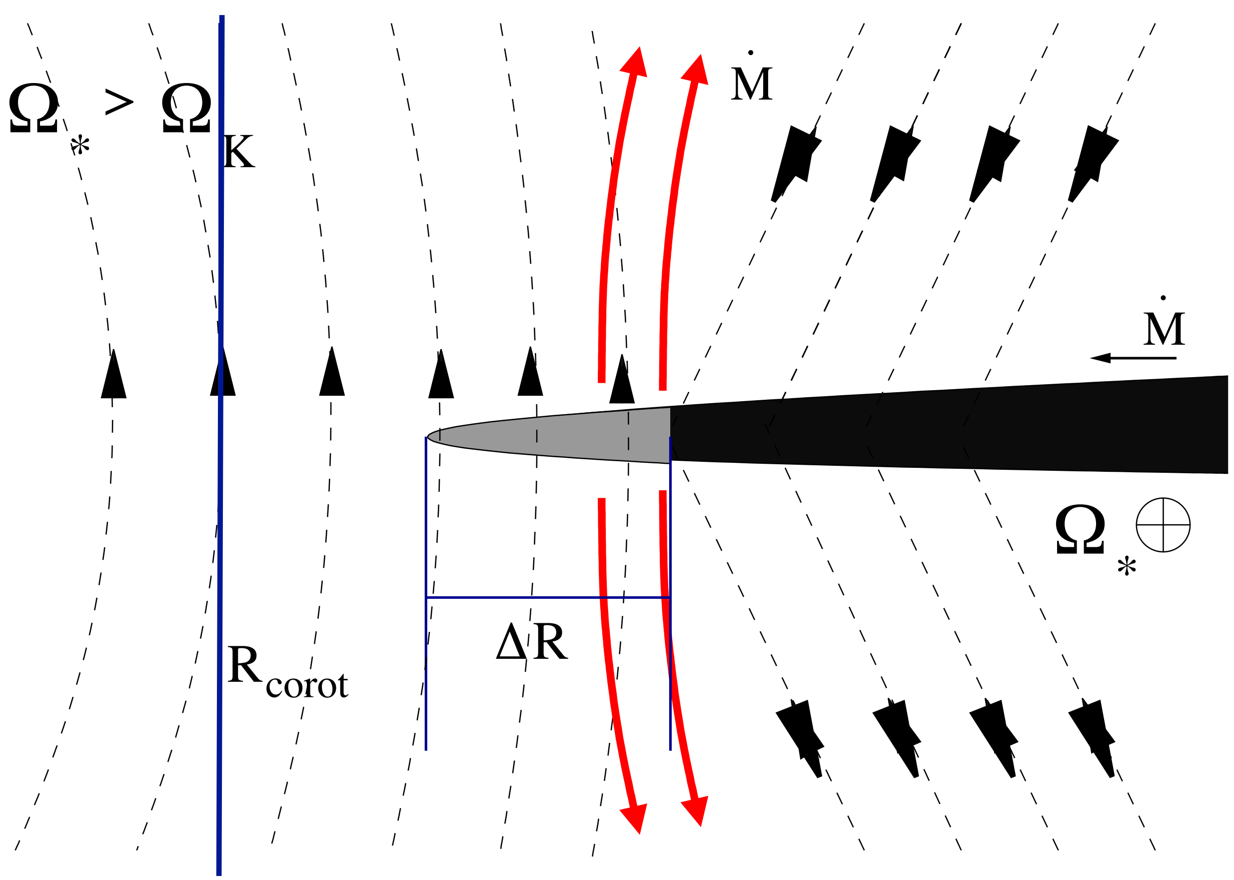
$$R_m > R_{corot}$$

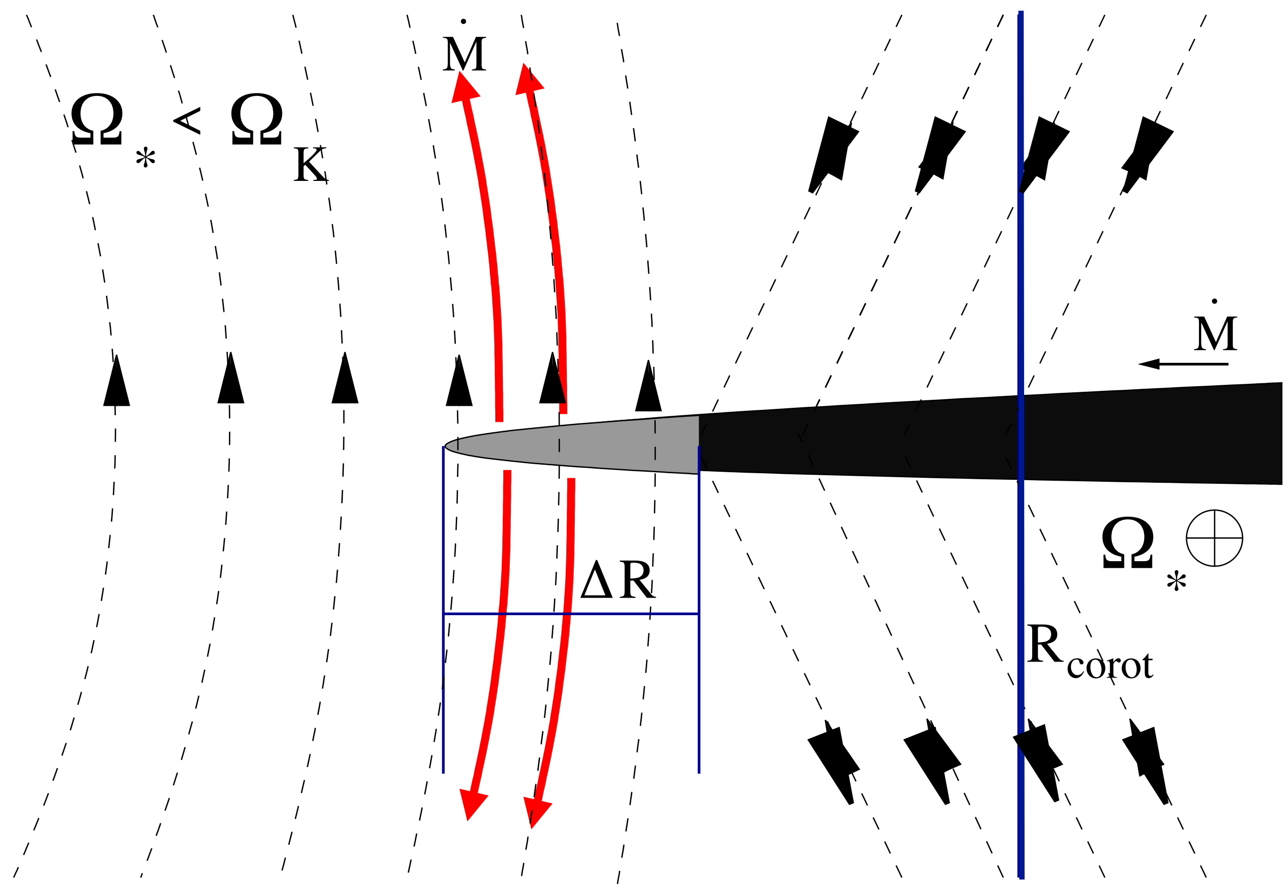


Episodic Accretion Bursts

Centrifugal barrier piles up gas near R_{corot}...

$$R_m > R_{corot}$$

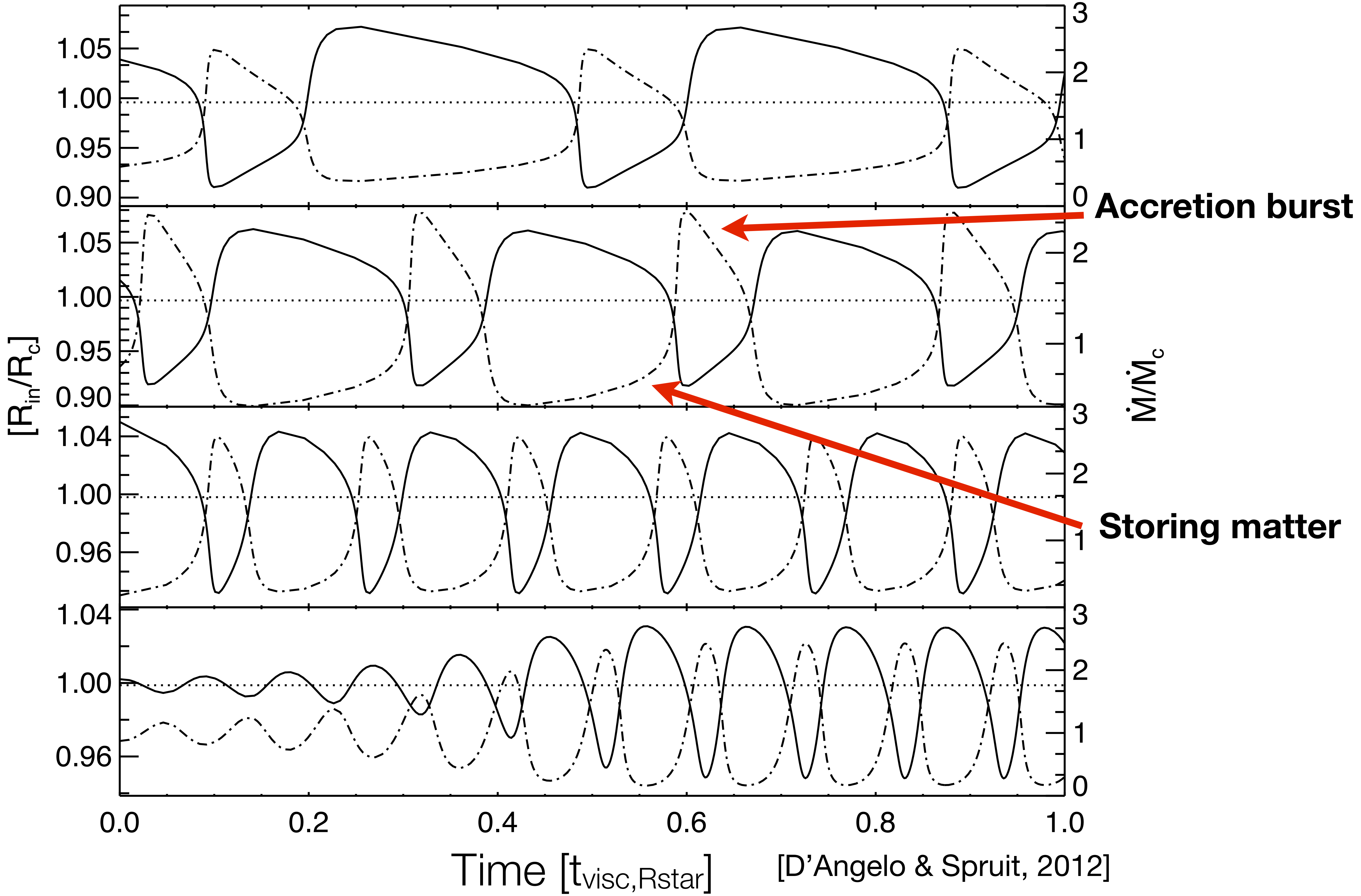




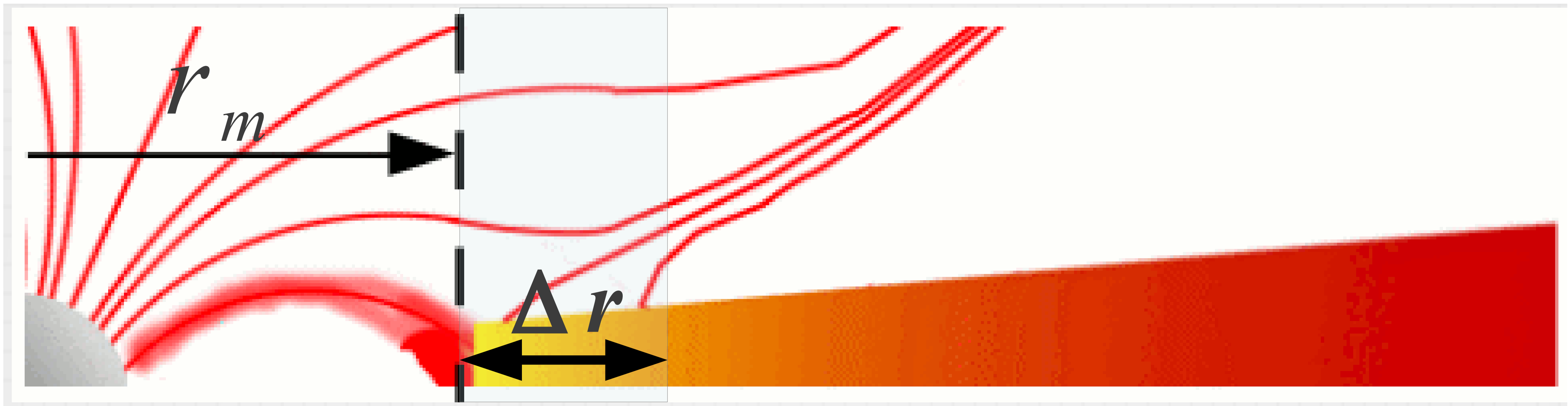
$$R_m < R_{corot}$$

...which eventually accretes onto the star as an outburst

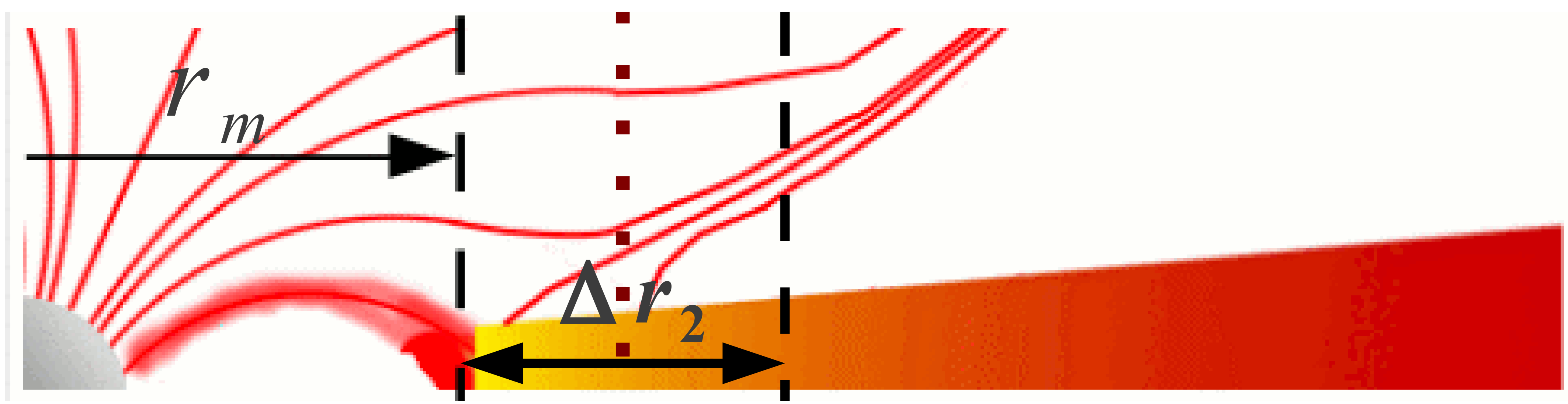
Examples of accretion bursts



Two parameters set instability duration/shape

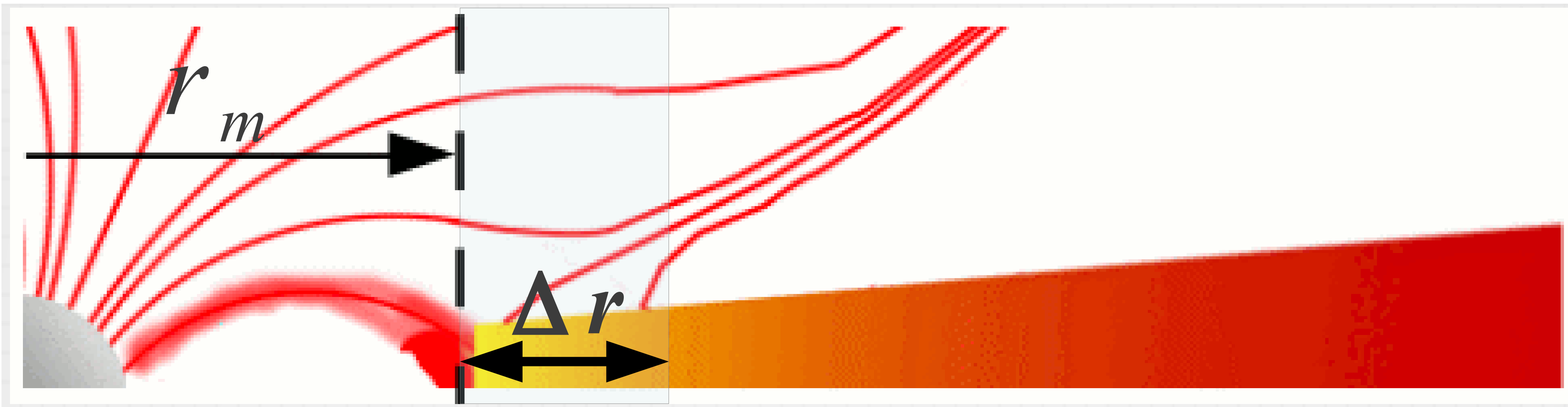


'Effective' coupled region between star and disc
(angular momentum transfer to disc)



Transition region between spin-up and spin-down solutions

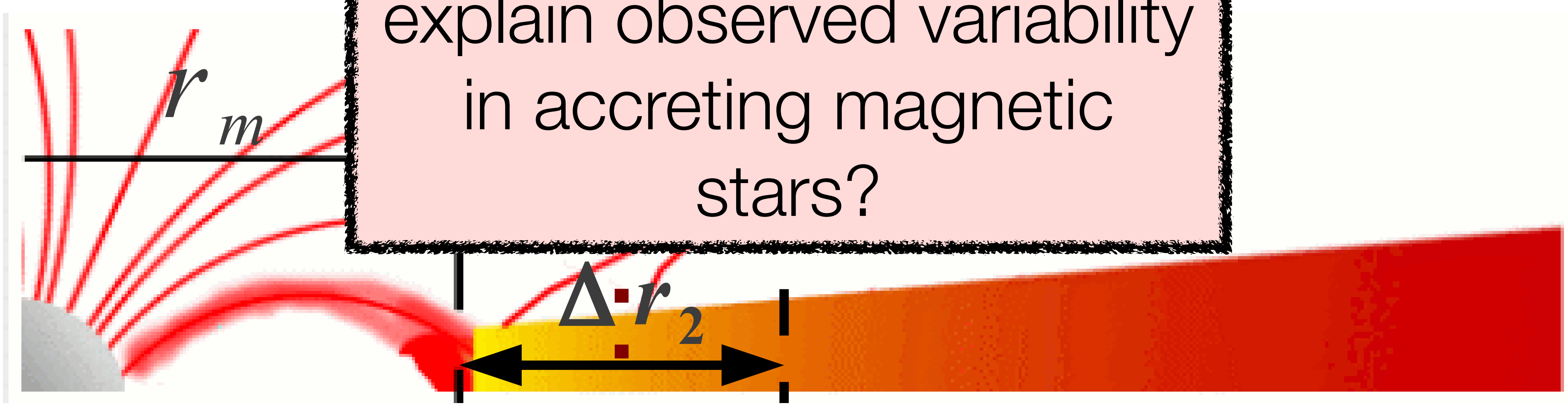
Two parameters set instability duration/shape



‘Effective’ coupled region between star and disc

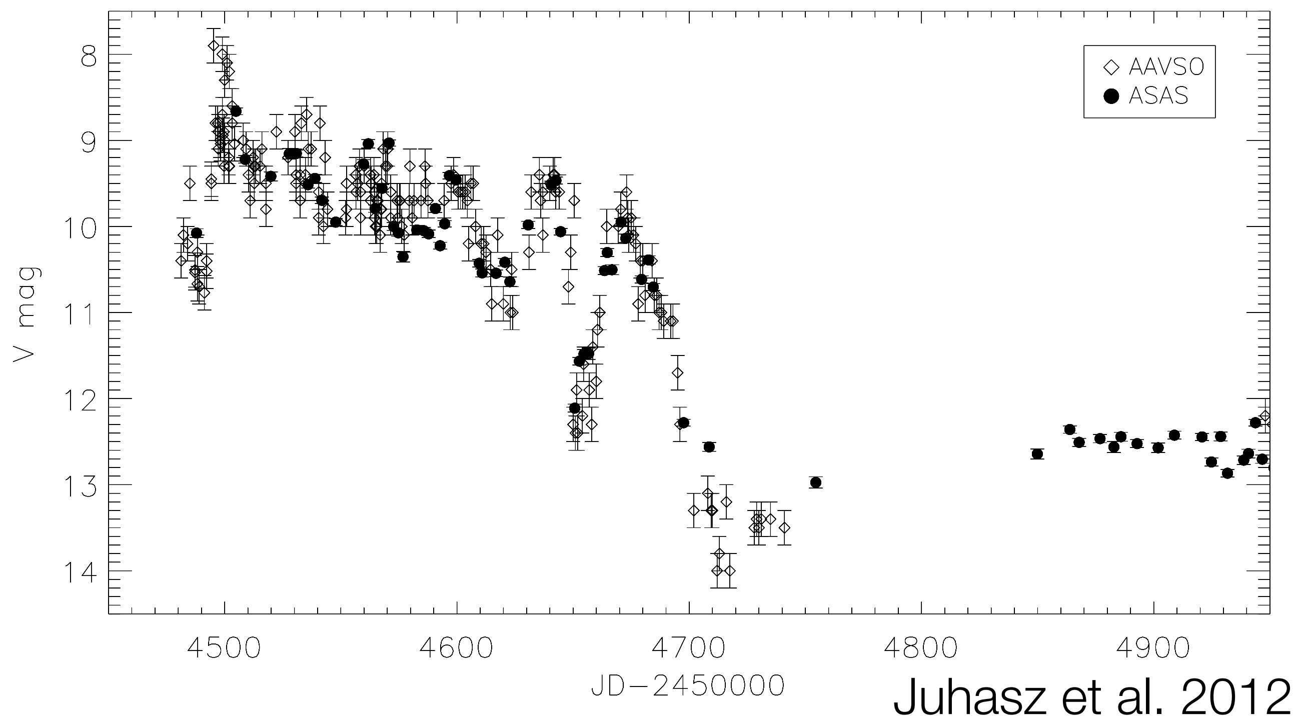
(angula c)

Can this mechanism explain observed variability in accreting magnetic stars?

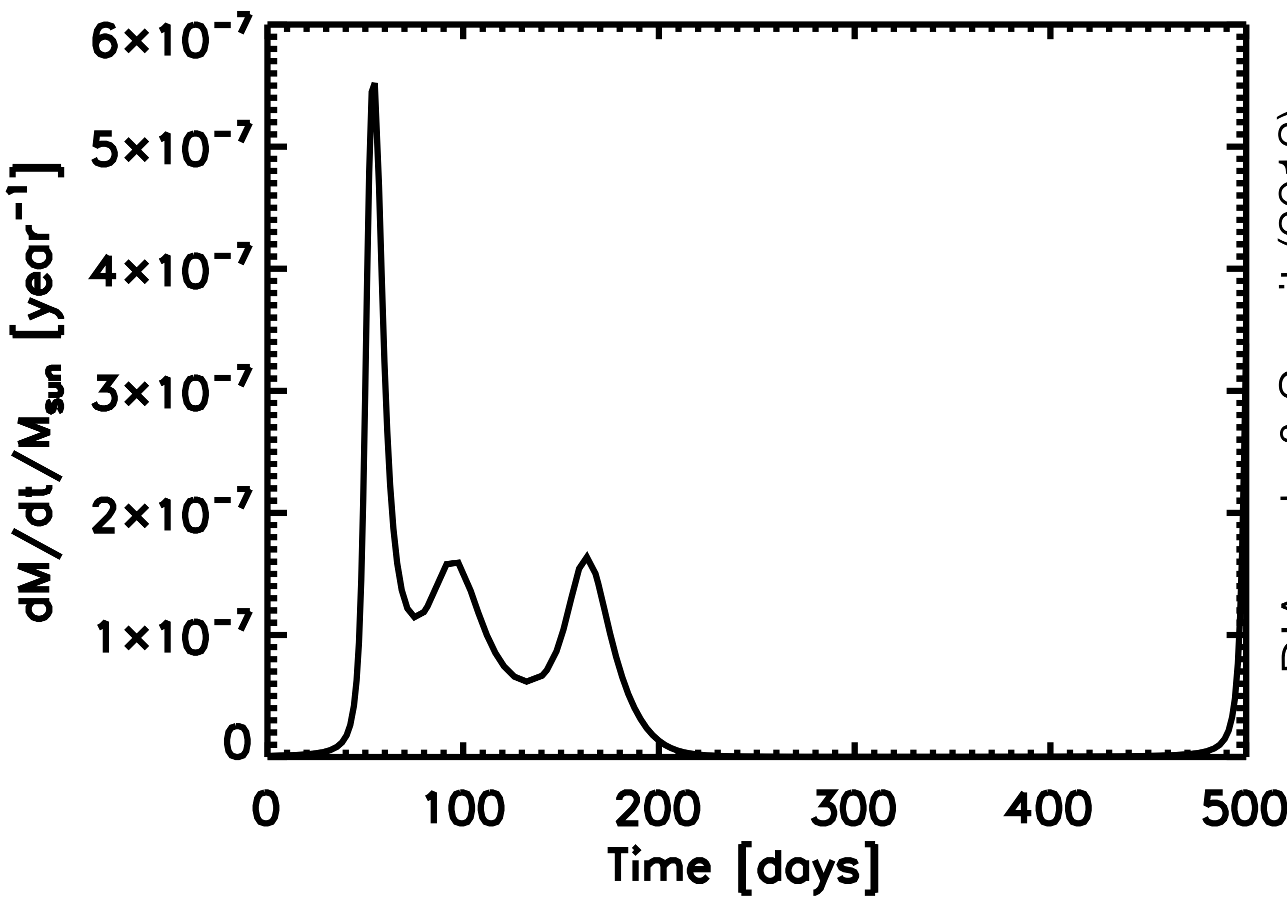


Transition region between spin-up and spin-down solutions

Accretion Variability in Young Stars



Juhasz et al. 2012



D'Angelo & Spruit (2012)

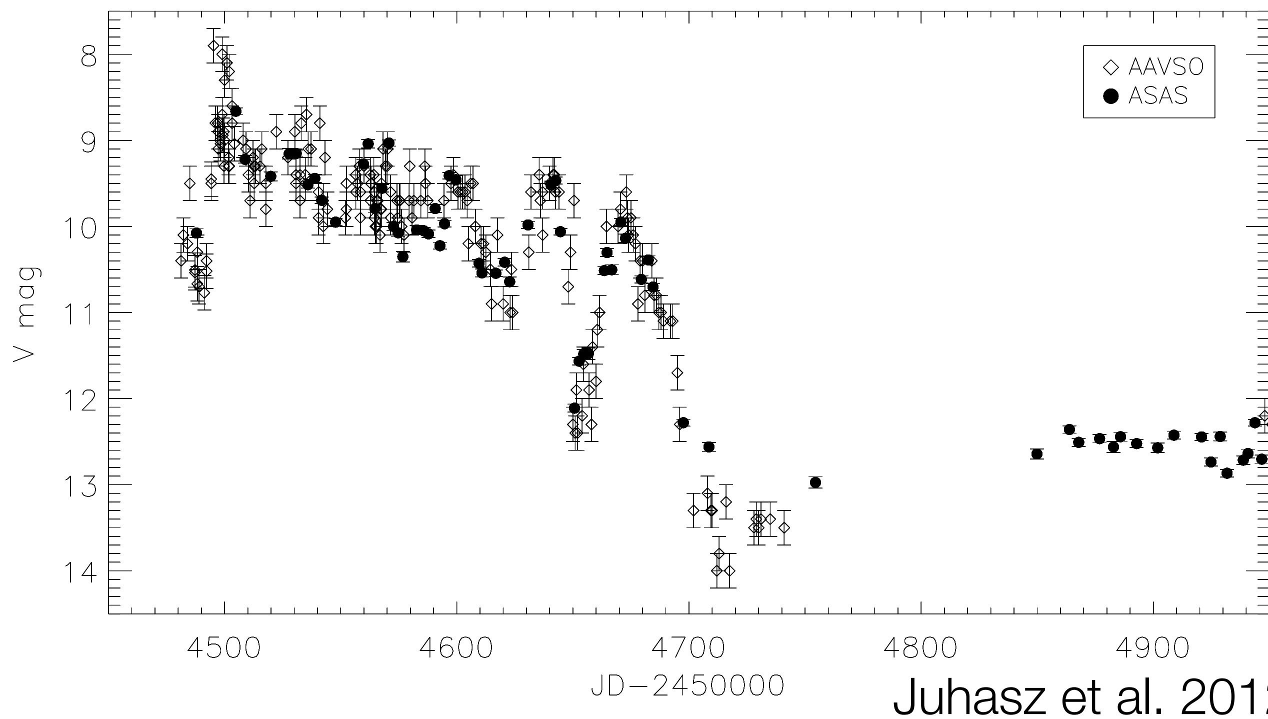
EX Lupi

TTauri star with outburst every 2-3yrs

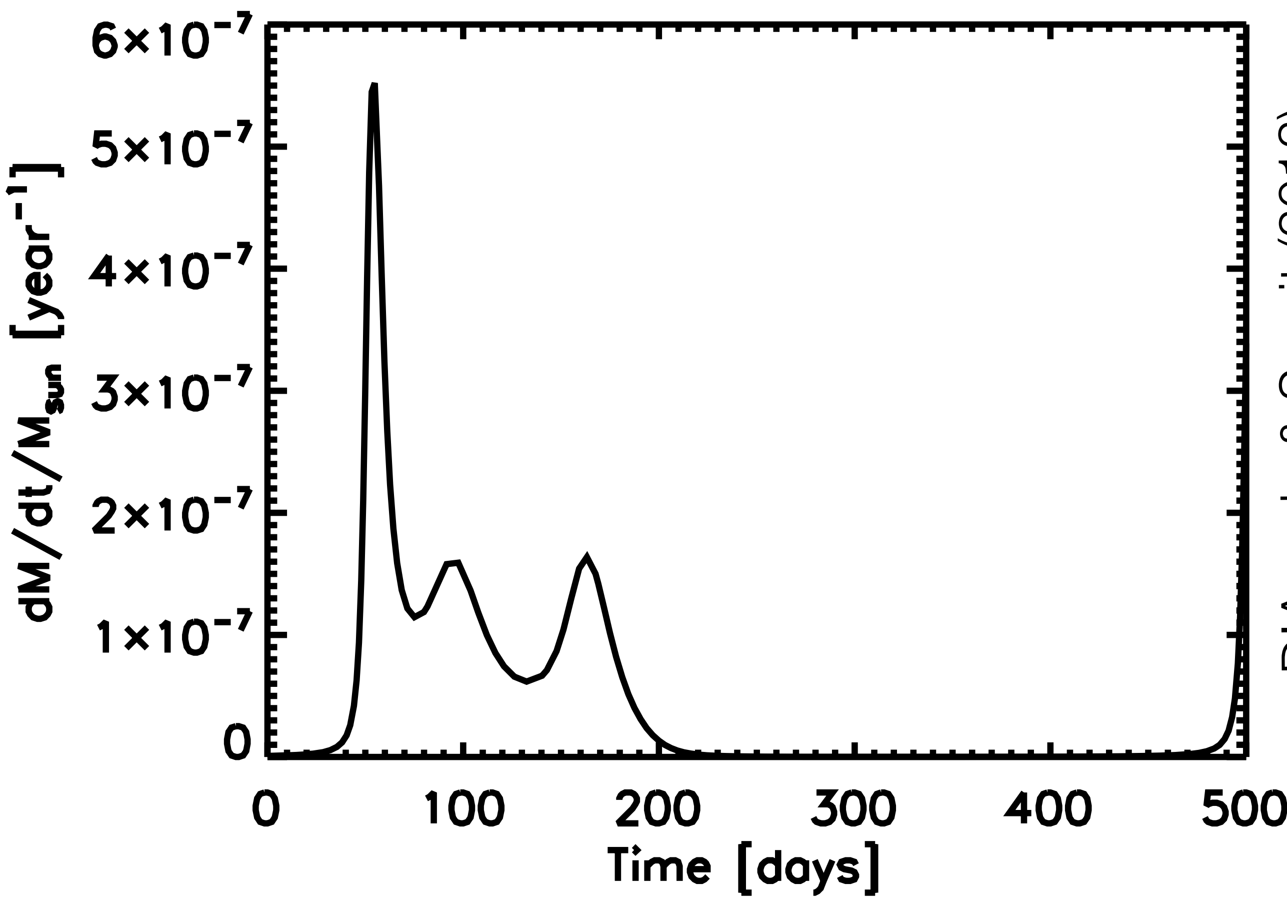
- 2008 outburst: x100 increase in luminosity V 10 mag (quiescent: 13-14)
- Duration ~300 days

Qualitative agreement with D'Angelo & Spruit (2010, 2012) model: accretion rate, burst shape, burst duration, recurrence time

Accretion Variability in Young Stars



Juhasz et al. 2012



D'Angelo & Spruit (2012)

EX Lupi

TTauri star with outburst every 2-3yrs

- 2008 outburst: x100 increase in luminosity V 10 mag (quiescent: 13-14)
- Duration ~300 days

Qualitative agreement with D'Angelo & Spruit (2010, 2012) model: accretion rate, burst shape, burst duration, recurrence time

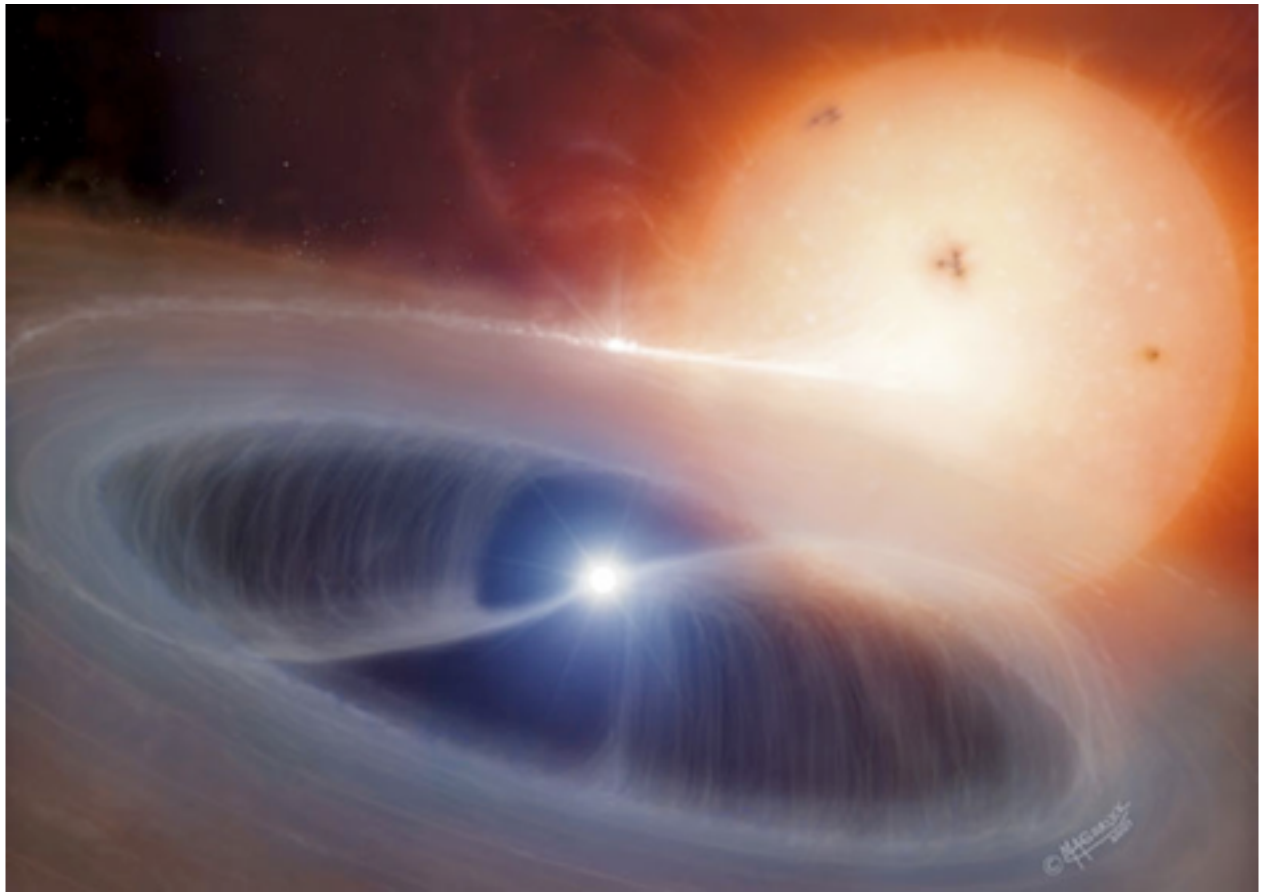
EXors: extreme of common behaviour? [Lorenzetti+ 2012]
New IR variability surveys [Scholz 2012]
Similar behaviour in other sources:
V2492 Cyg, [Hillenbrand+ 2013]
V1647 Ori [Mosoni + 2013]

Accreting ms X-ray Pulsars

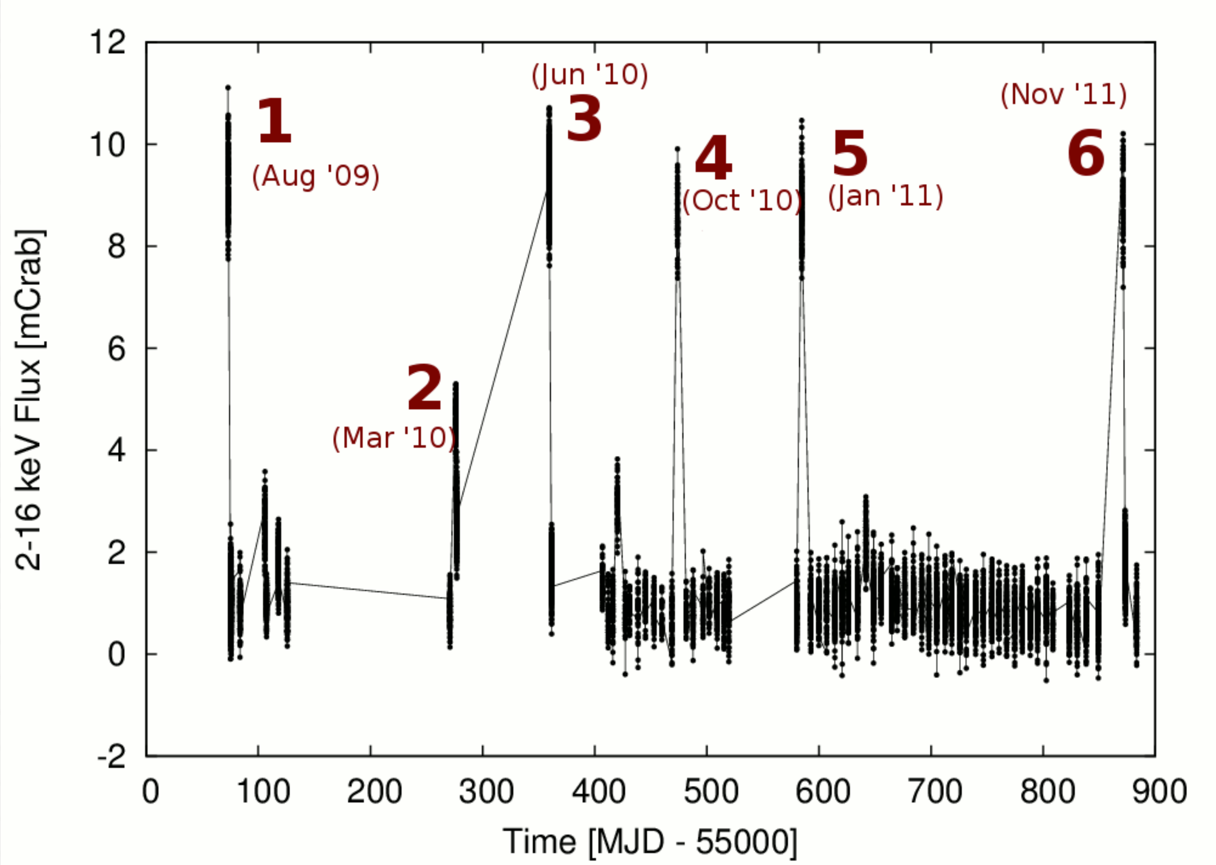
- Transient X-ray binaries (L_x 10^{32}-10^{38} ergs/s)

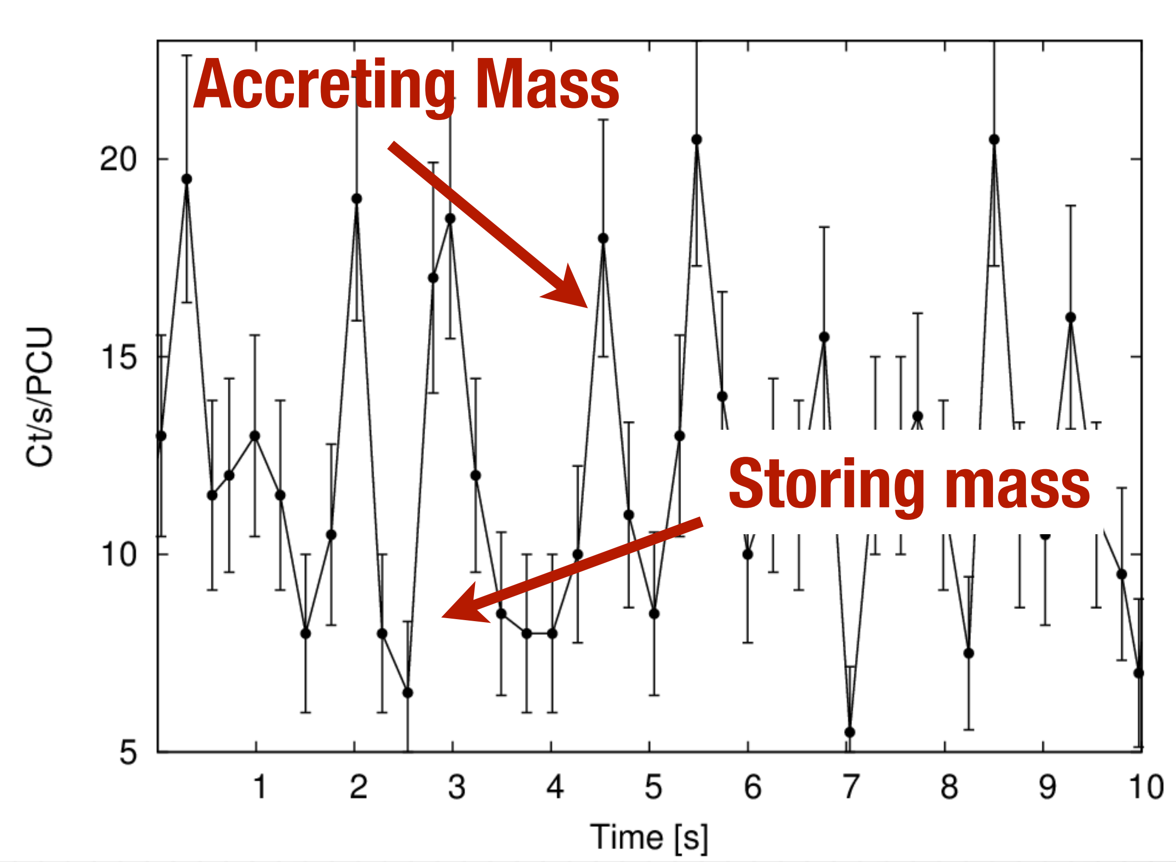
- Neutron star host with *small magnetic fields* (10^8-10^9 G) and coherent pulsations (proof of magnetospheric accretion); sometimes *transient* pulsations (Aql X-1)

- Except for coherent pulsations, resemble *Atoll* sources (NS hosts with undetected fields): suggest disc truncation could be common (especially at low accretion rates)



NGC 6440 X-2: QPOs and recurrent outbursts

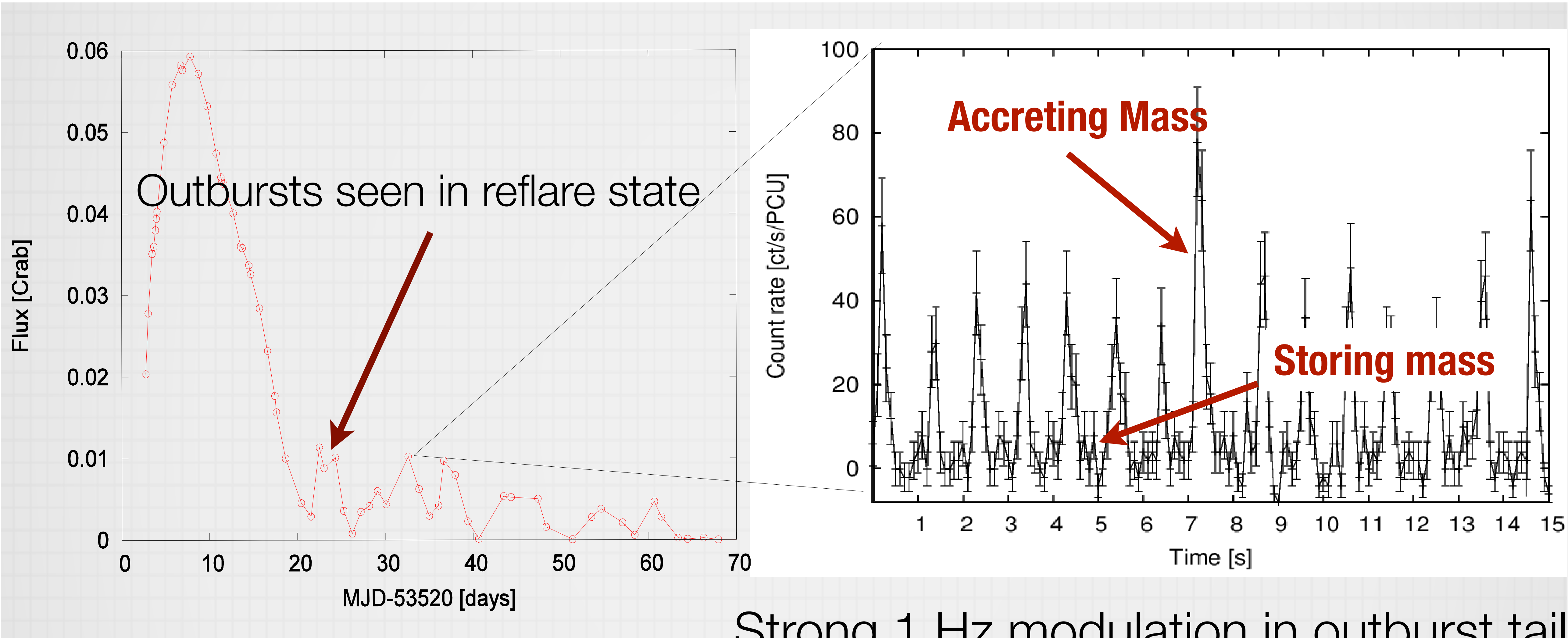




Patruno & D'Angelo '13
Altamirano+ 10; Heinke+ 11;

Spin Period: **5 ms**
Orbital Period: **1 hr**
Recurrence Time: **variable**

SAX J1808.4-3658



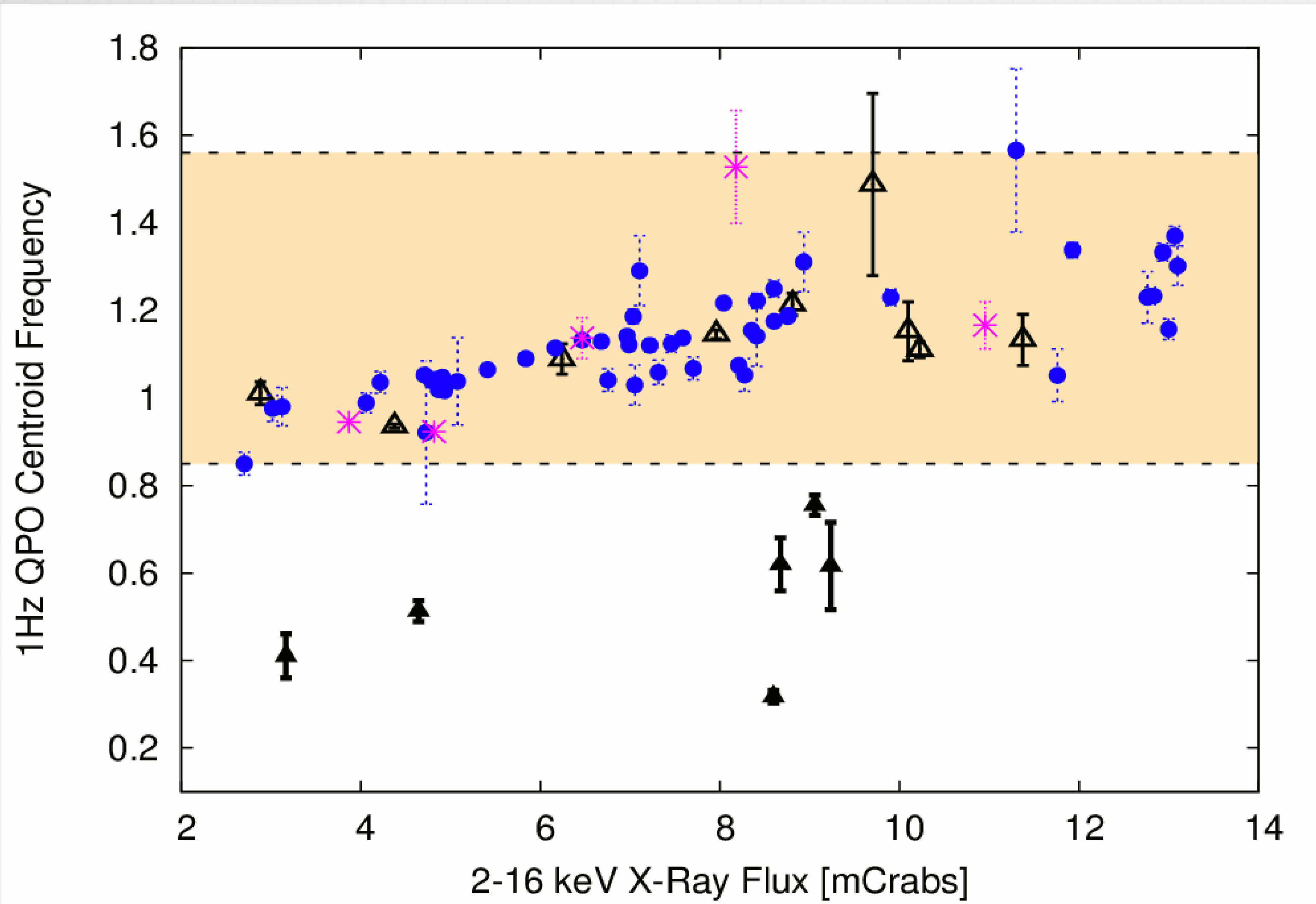
Patruno et al. 2009
van der Klis 2000

Strong 1 Hz modulation in outburst tail of several outbursts

Spin Period:	**2.5 ms**
Orbital Period:	**2 hr**
Recurrence Time:	**2-3 yr**

Instability Timescales

QPO Frequency vs. X-ray flux



$$T_{visc} \propto 80\,\alpha^{0.1}\,\dot{M}^{-3/10}\,r^{5/4}\,s$$

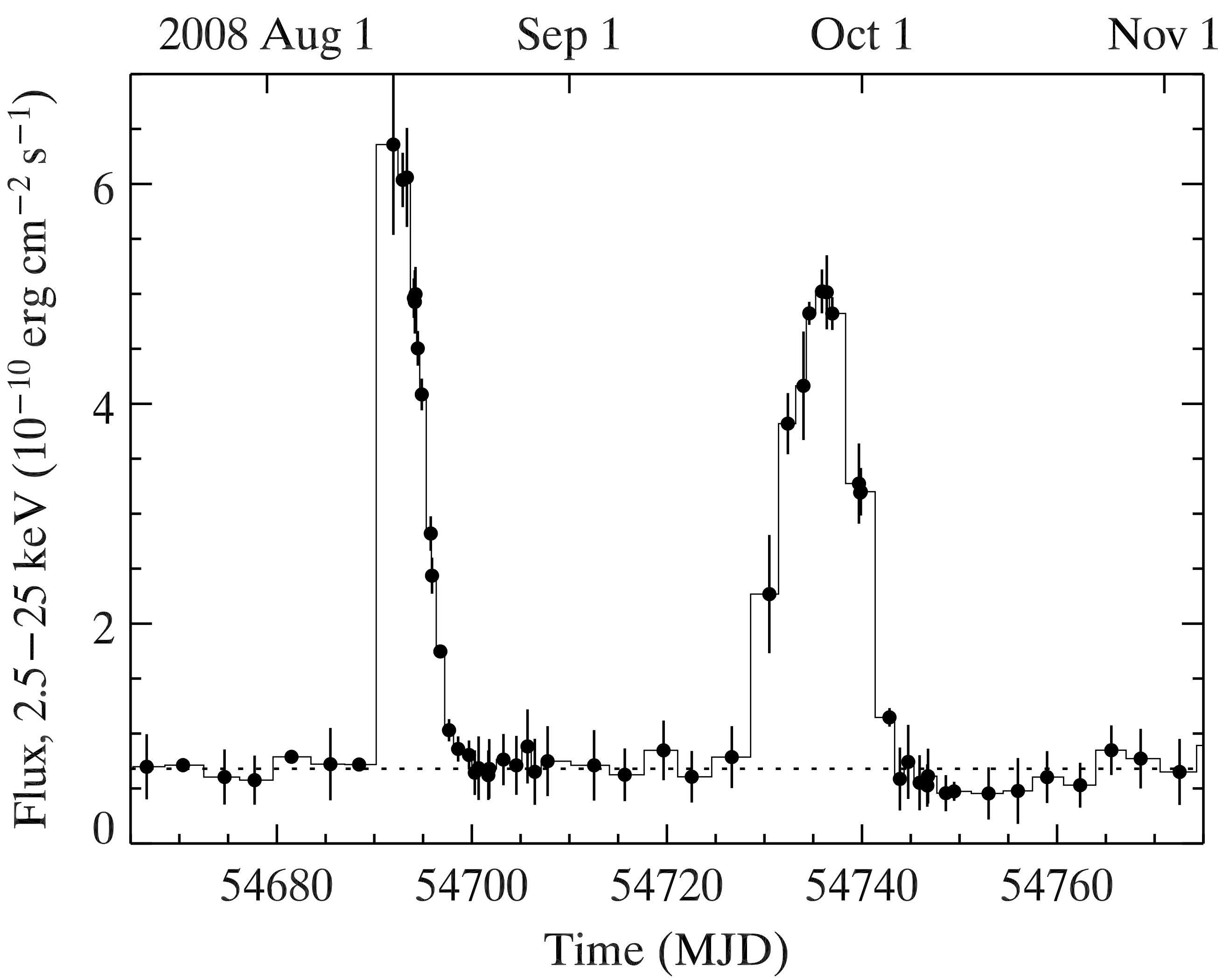
$r \approx r_m$ → 50 km (NGC6440 X2), 30 km (SAX J1808)

$$\tau_{inst} \approx 0.01 - 0.1\,T_{visc}$$

$$\nu_{inst} \approx 0.1 - 1\,Hz$$

Patruno & D'Angelo 2013

Weak Recurrent Outbursts?



Hartman et al., 2011

Interplay between ionization instability and disc-field interaction

New evidence for dead disc: **weak, rapidly recurring outbursts**

Gas remains in inner disc during brief quiescence

IGR J00291+5934 (Hartman et al. 2011)

NGC 6440 X-2 shows similar behaviour (Heinke et al. 2010)

Reflares in SAX J1808.4-3658

Persistent NS sources?

Long-term Evolution of a Dead Disc

What happens when accretion rate decreases?

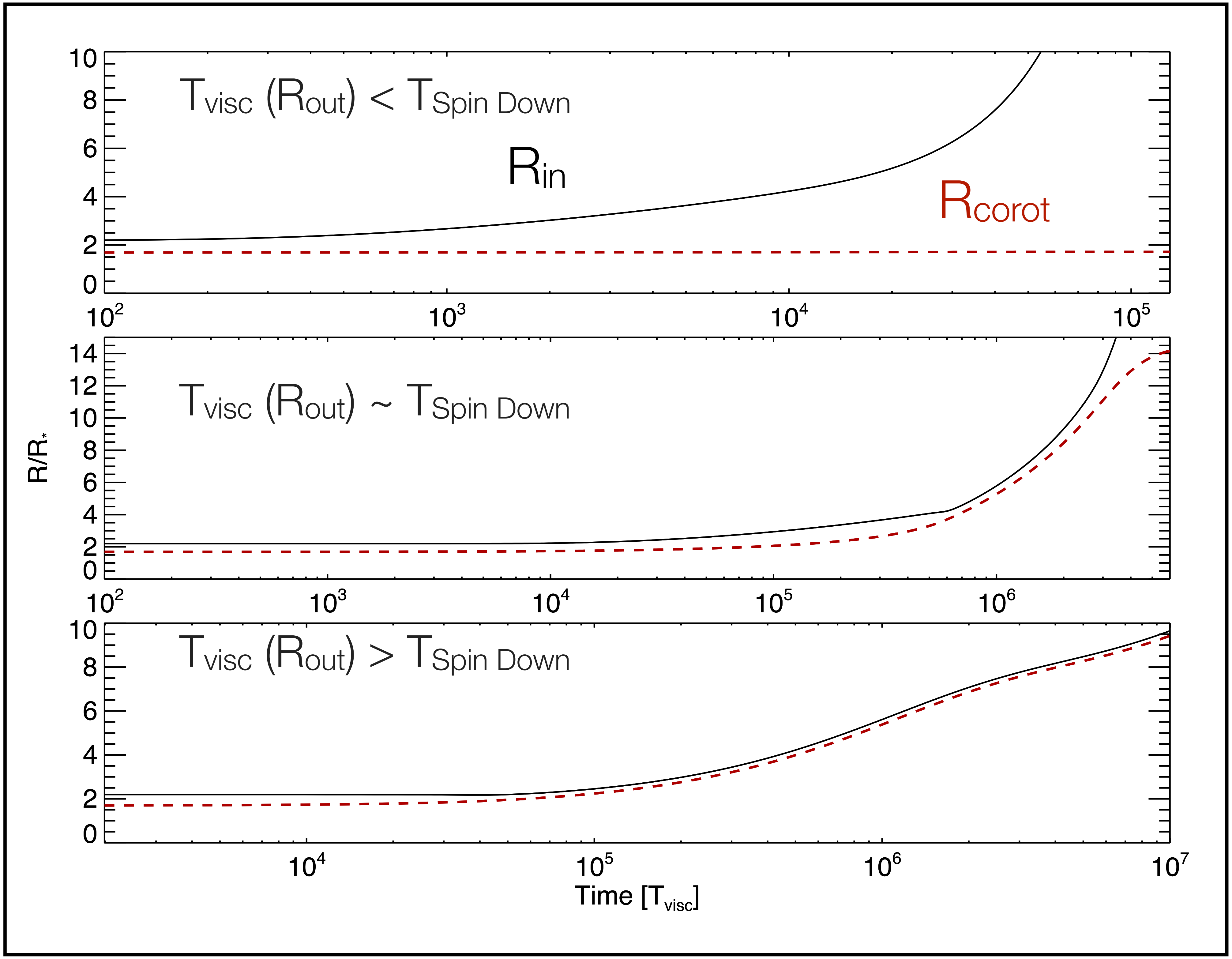
Propeller: disc is expelled; R_m moves far from R_{corot}
Dead Disc: inner disc stays near R_{corot} – spin-down can continue **indefinitely**

$$T_{\rm visc} \sim \frac{r^2}{\nu} \sim \frac{P_k}{\alpha(H/r)^2} \sim 10^3 - 10^5 P_k$$

$$T_{\rm SD} \sim \frac{GM_* I}{\Omega_f \beta \mu^2} \sim 10^7 T_{\rm visc}$$

Relevant Timescale: ratio of **viscous** and **spin-down** timescale in the disc

Spin down efficiency I: Disc Size



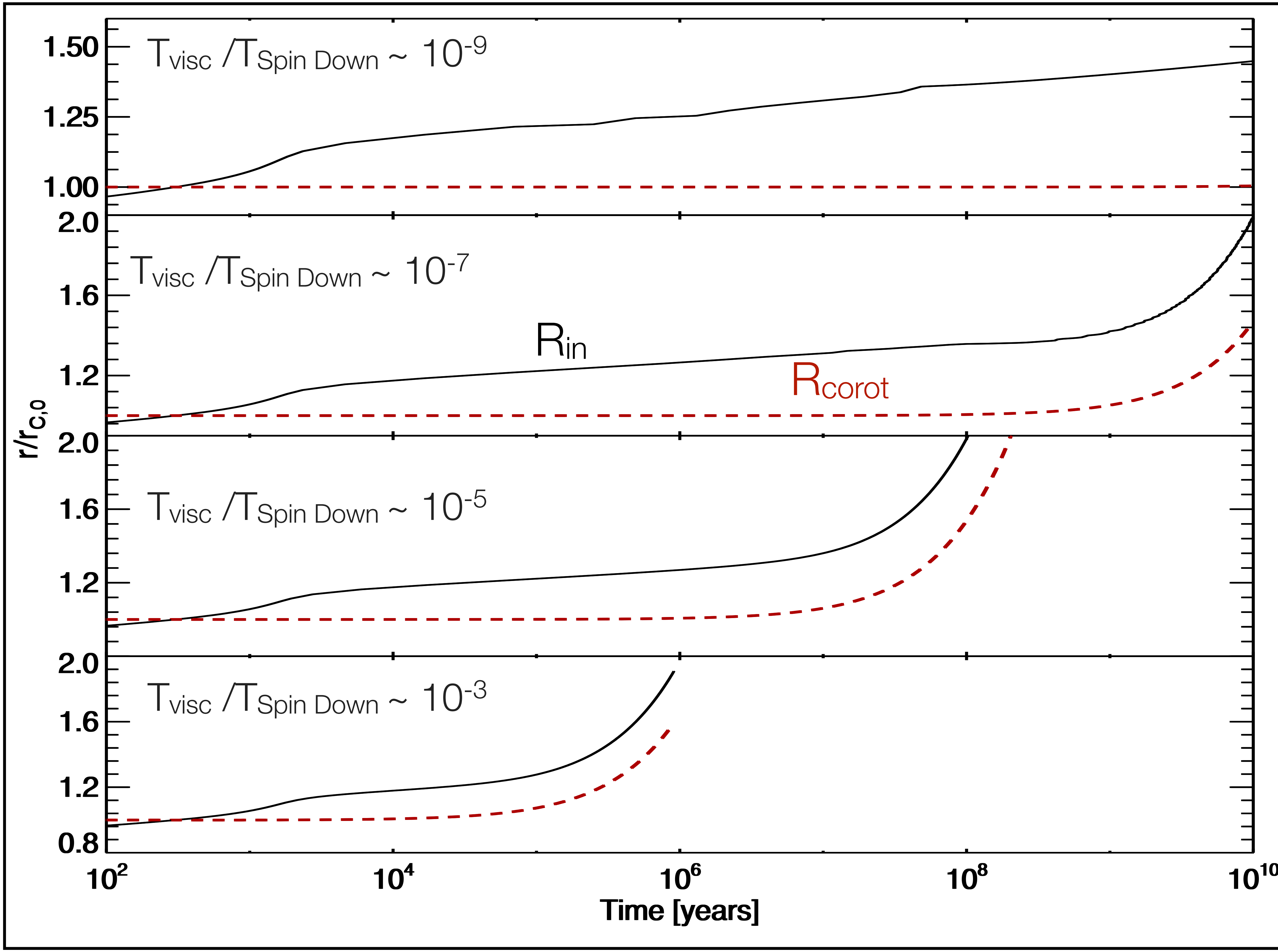
D'Angelo & Spruit 2011

Small disc: no spin-down

Mid-sized disc: eventual decoupling

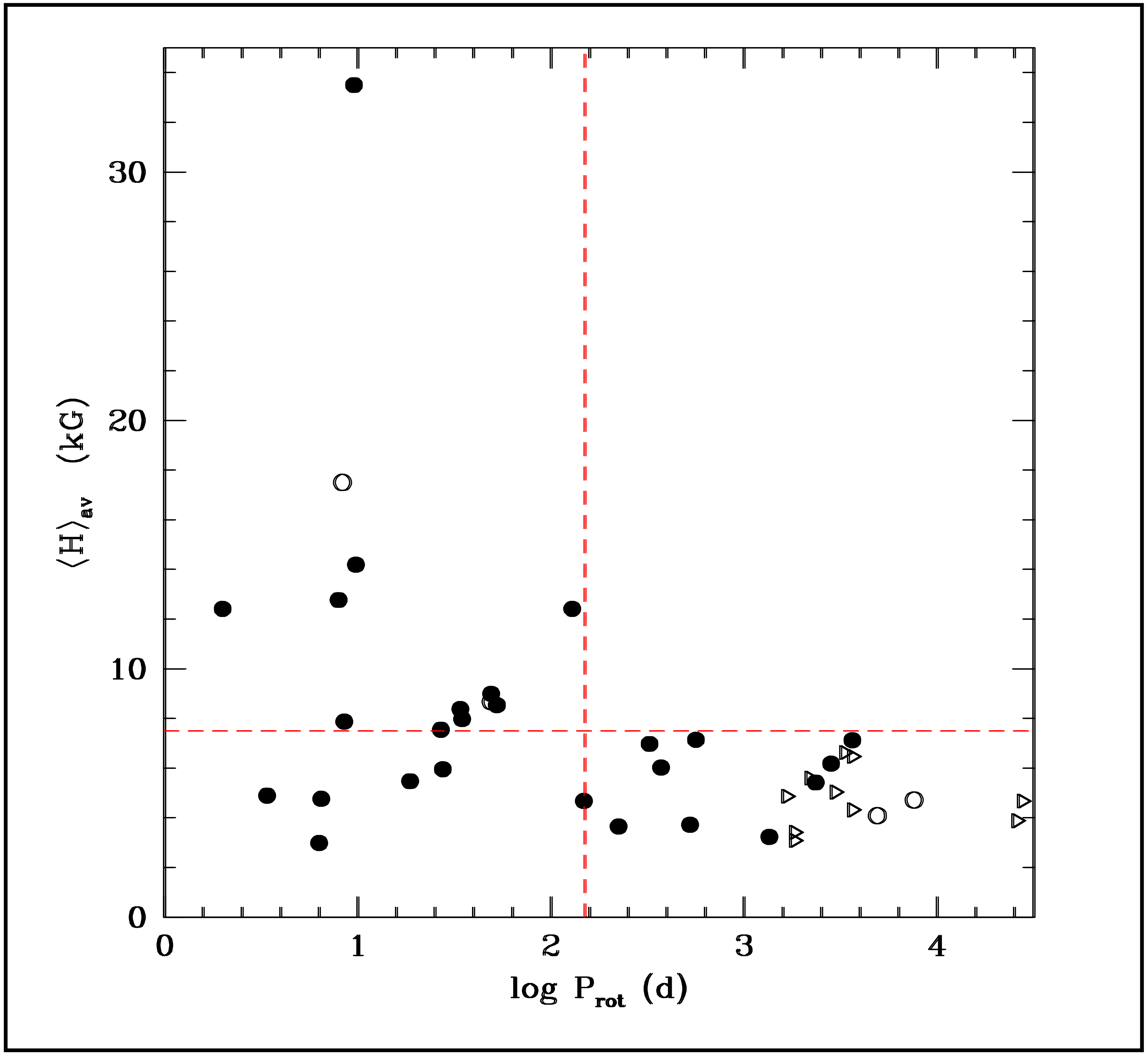
Large disc: efficient spin-down

Spin down Efficiency II: “Stiffness” in the disc



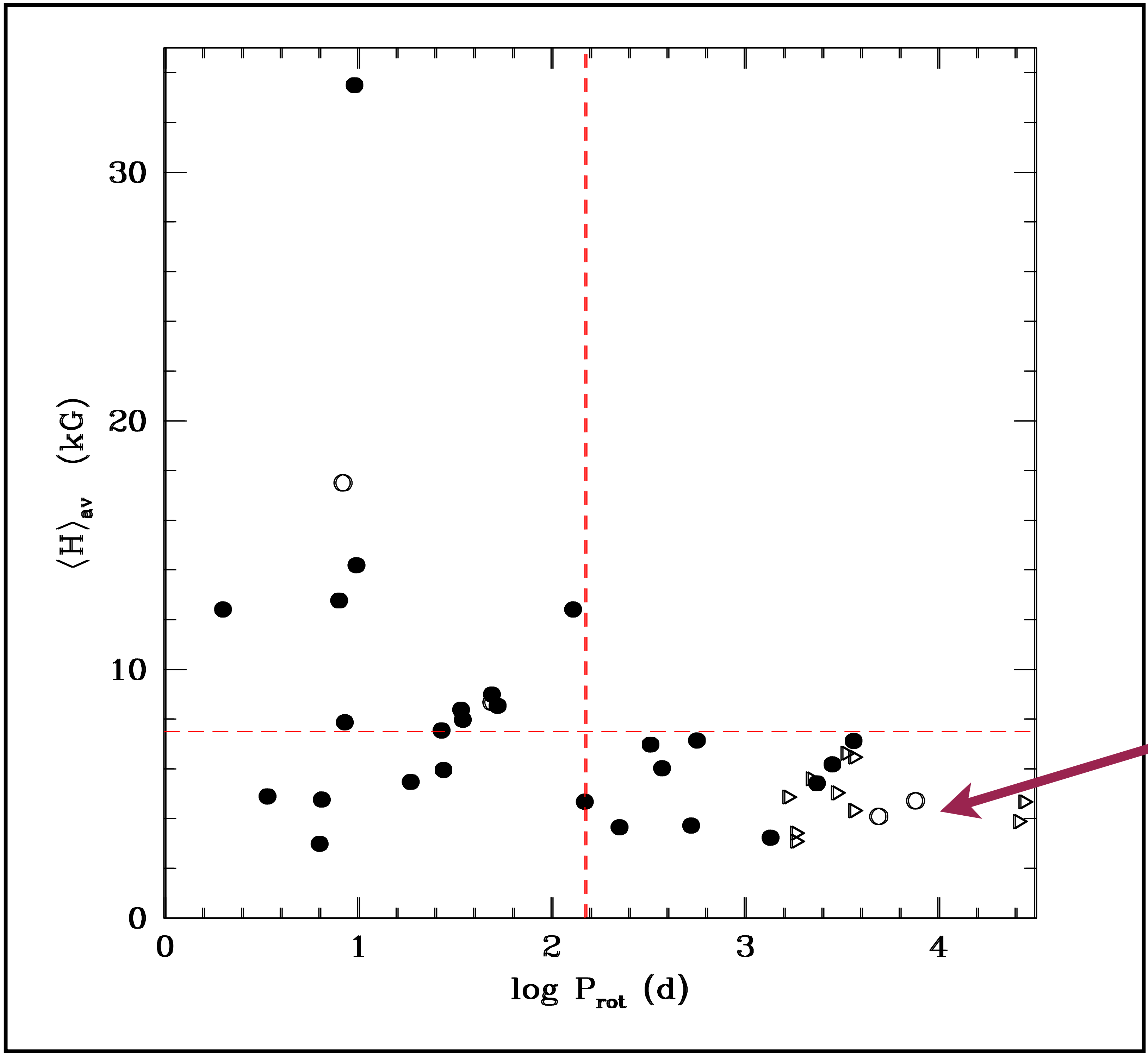
D’Angelo & Spruit 2011

Ap stars are slow rotators: residual dead discs?



(Mathys 2008)

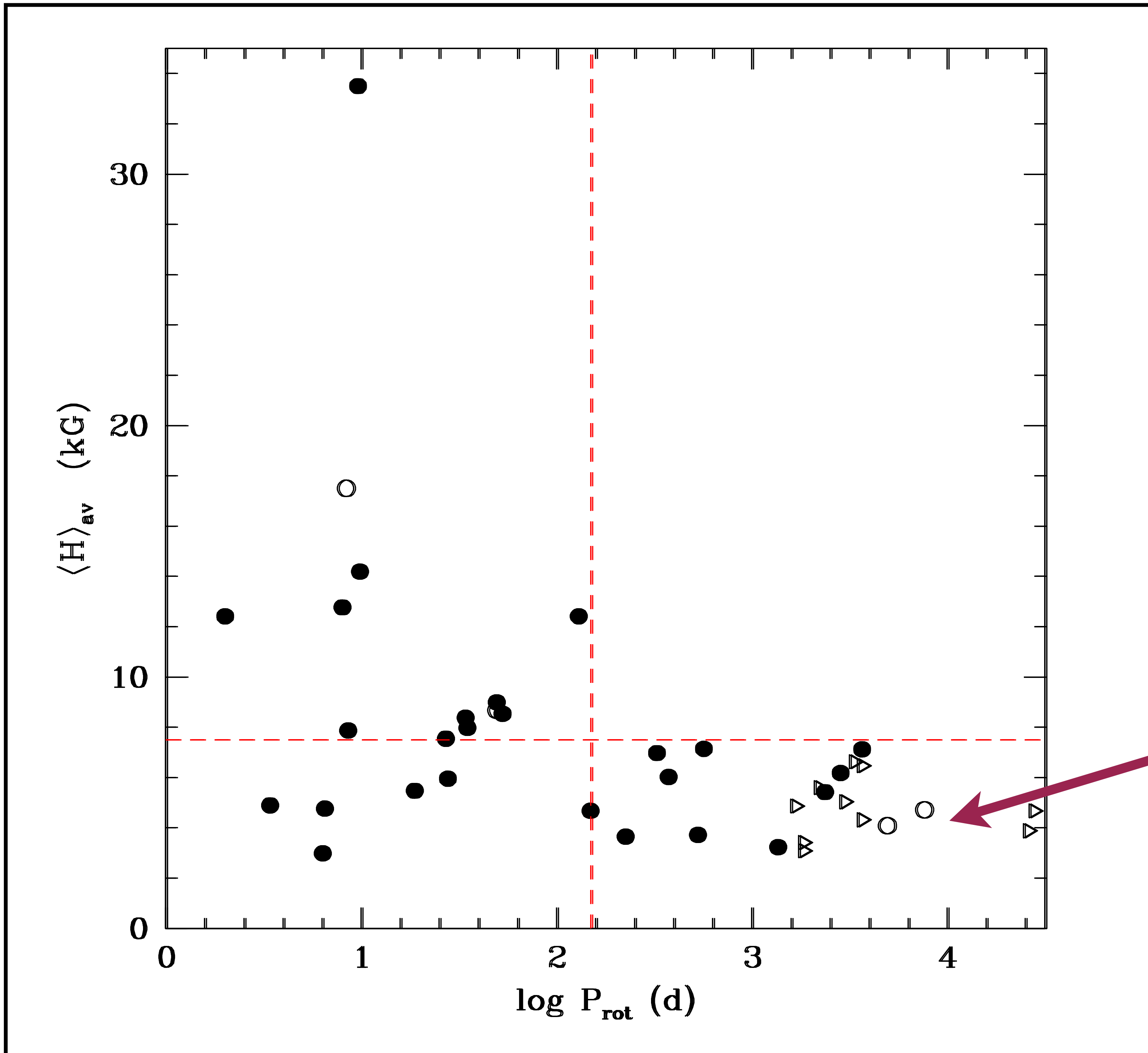
Ap stars are slow rotators: residual dead discs?



Spin periods span > *4 orders of magnitude*

(Mathys 2008)

Ap stars are slow rotators: residual dead discs?

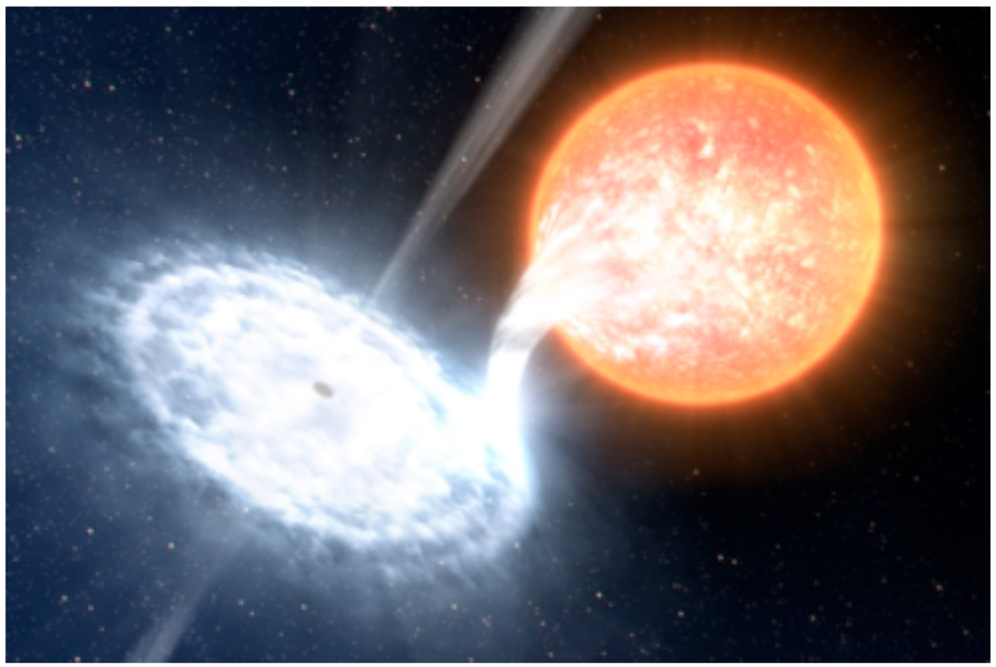


Slowest Rotators are *binaries* (sink for stellar angular momentum)

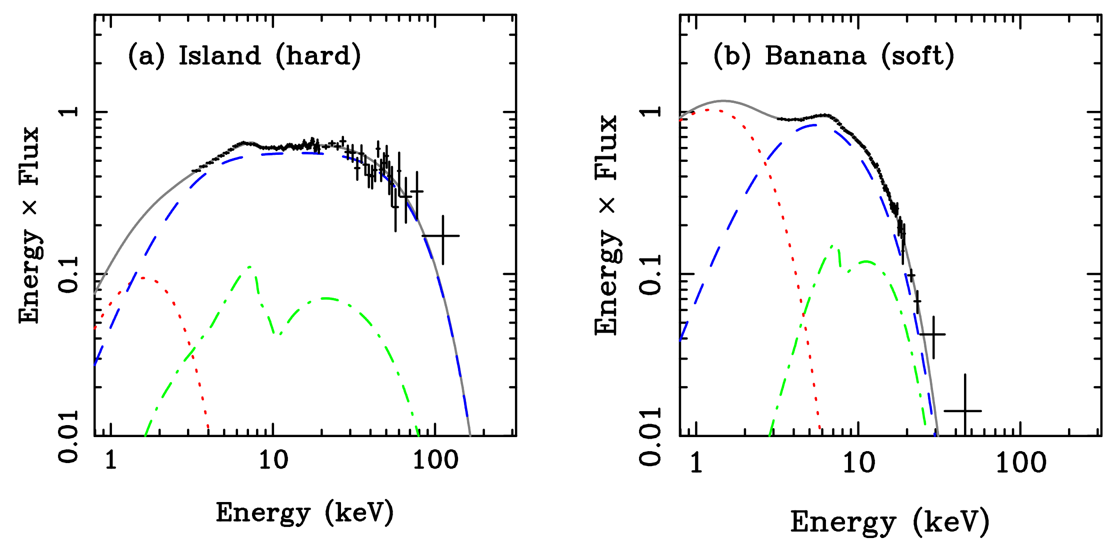
Spin periods span > *4 orders of magnitude*

(Mathys 2008)

Accreting Compact Binaries at low luminosity



Unknown how accretion works at low accretion rates ('Radiatively-Inefficient Flows')



Neutron star vs. Black Hole:

boundary (surface of star) and *magnetic field* (truncates disk)

Magnetospheric accretion can be used to test RIAFs

Radiatively-Inefficient Accretion Flows and magnetic fields

disk

$$L_x \propto \frac{GM\dot{M}}{8\pi R^3} \propto \dot{M}^{13/7}$$

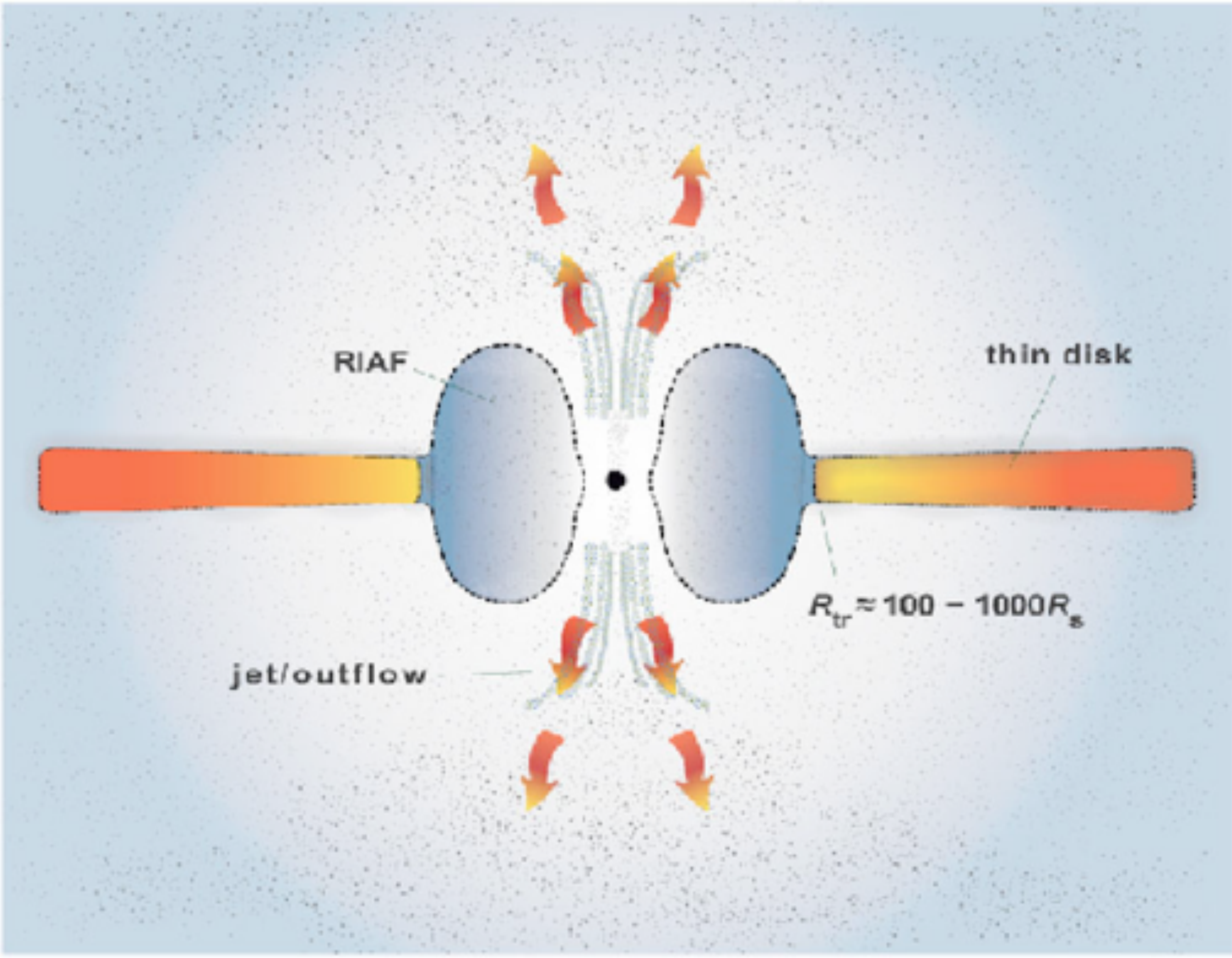
surface

$$L_x \propto \dot{M}$$

For same accretion rate, RIAFs much dimmer than thin disks

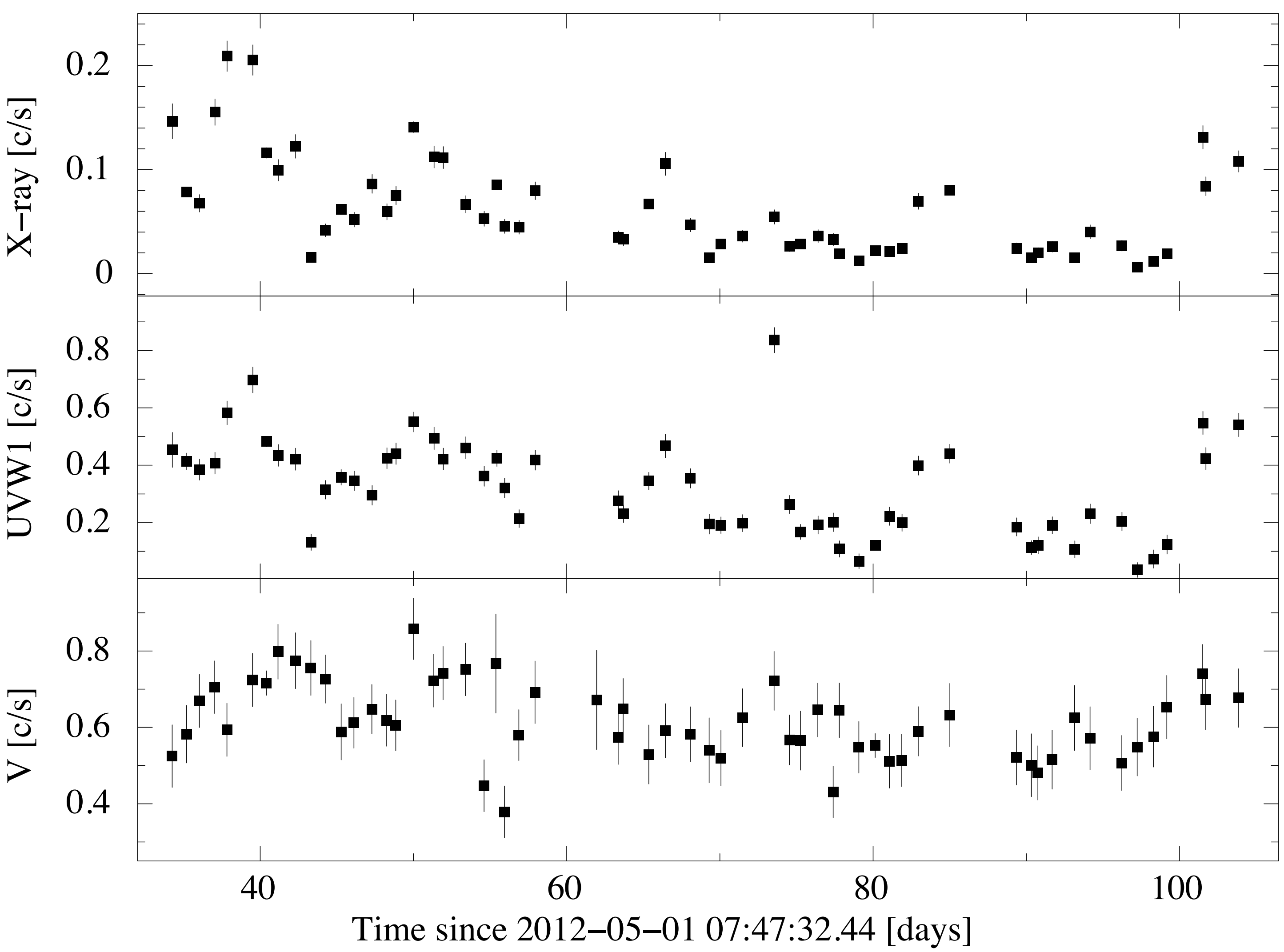
A RIAF is barely bound: easier to drive outflow (propeller)

For disks truncated by magnetosphere, luminosity mostly determined by material falling onto star



Cen X-4 and quiescent LMXBs: Accretion puzzles at low $\dot{M}$

'Quiescent' NS:
$L_X \sim 10^{32}$-10^{33} erg/s



(Bernardini et al. 2013)

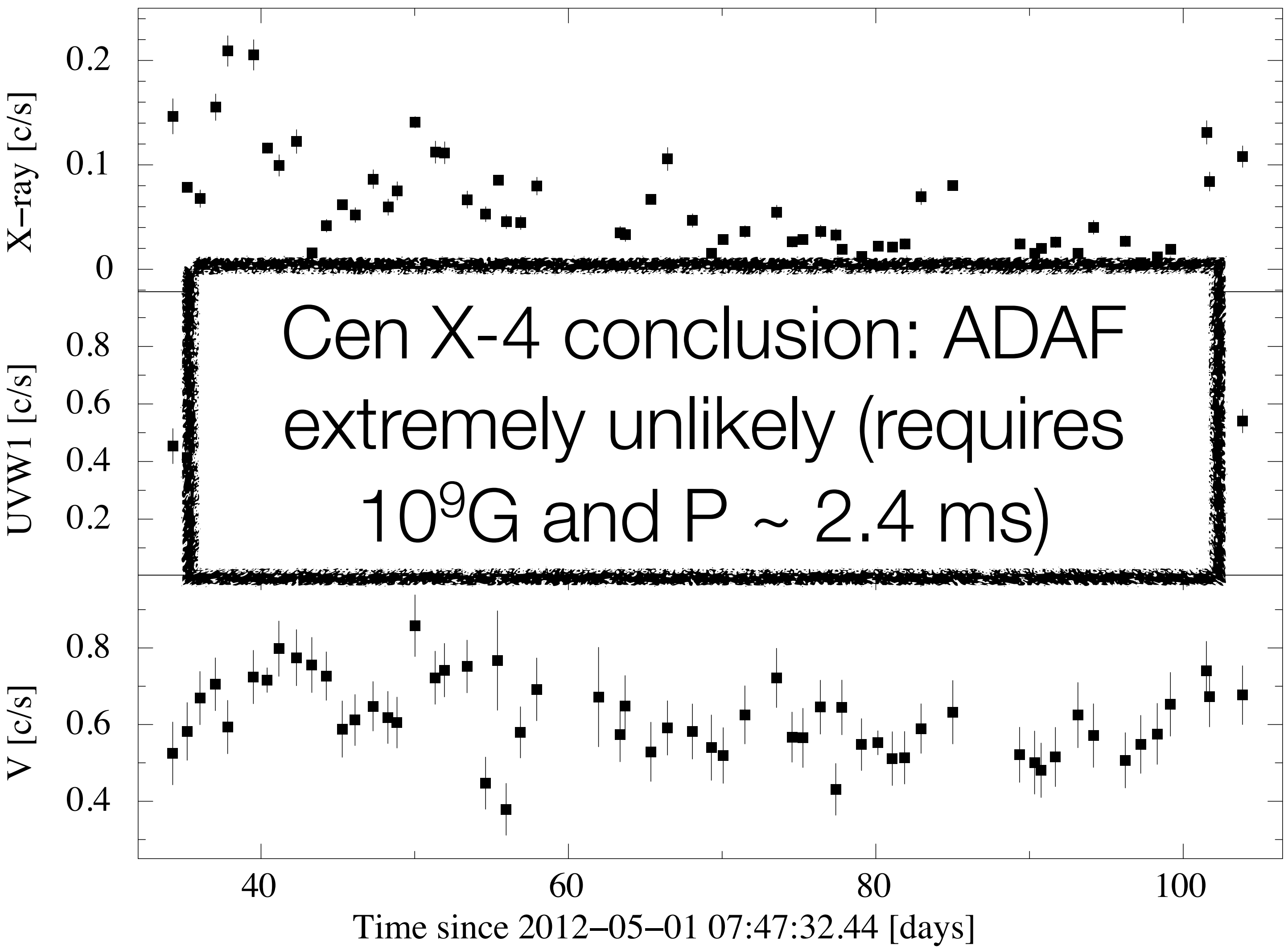
Rapid variability and X-ray spectrum suggests continued accretion in "strong propeller" regime (assuming $B \sim 10^8$G, $L_X \sim 10^{35}$erg/s)

From magnetosphere + hard surface assumption, could constrain RIAF models (e.g. outflow vs. ADAF)

Many NS remain persistently accreting at low rates: could a dead disk inhibit transition to RIAF?

Cen X-4 and quiescent LMXBs: Accretion puzzles at low $\dot{M}$

‘Quiescent’ NS:
$L_X \sim 10^{32}$-10^{33} erg/s



Cen X-4 conclusion: ADAF extremely unlikely (requires 10^9G and P ~ 2.4 ms)

(Bernardini et al. 2013)

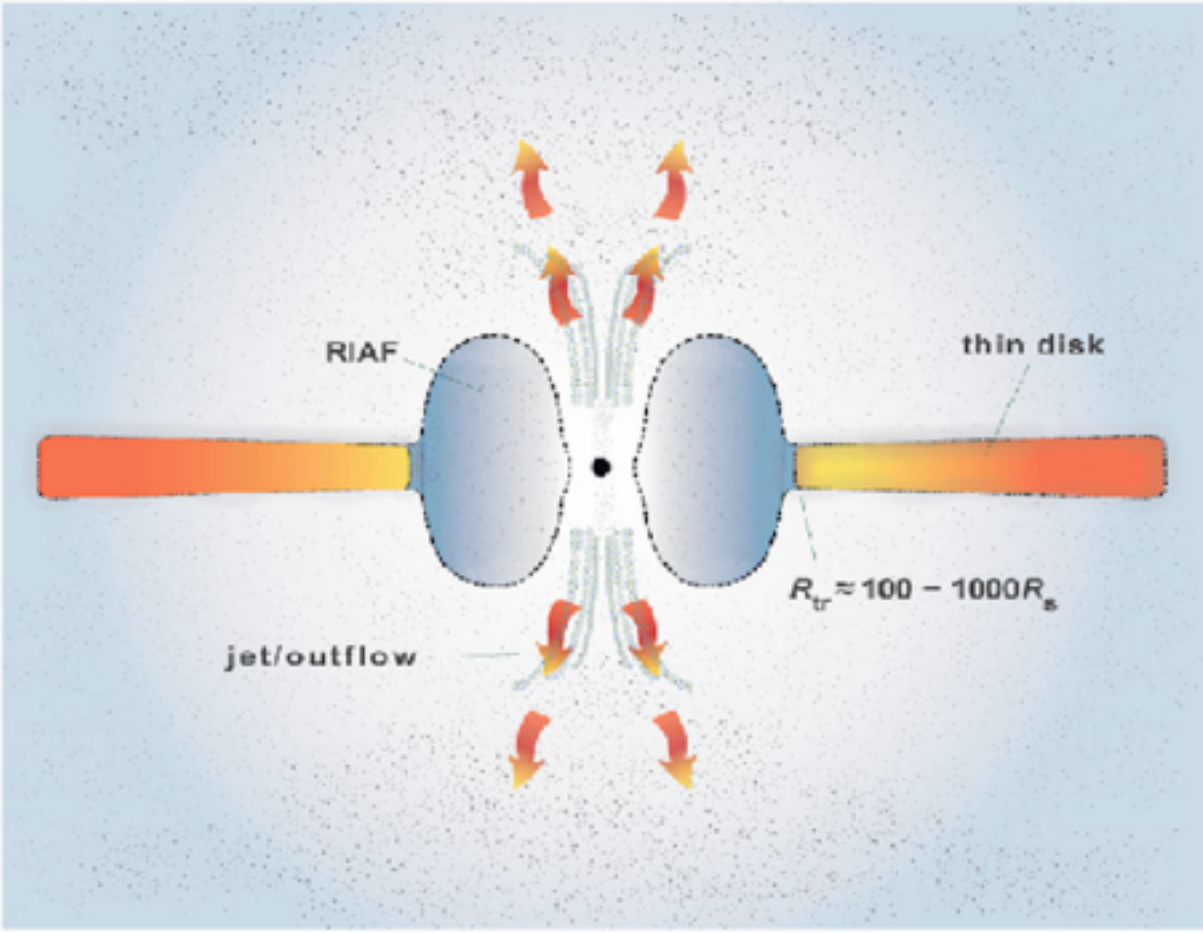
Rapid variability and X-ray spectrum suggests continued accretion in “strong propeller” regime (assuming B~10^8G, $L_X \sim 10^{35}$erg/s)

From magnetosphere + hard surface assumption, could constrain RIAF models (e.g. outflow vs. ADAF)

Many NS remain persistently accreting at low rates: could a dead disk inhibit transition to RIAF?

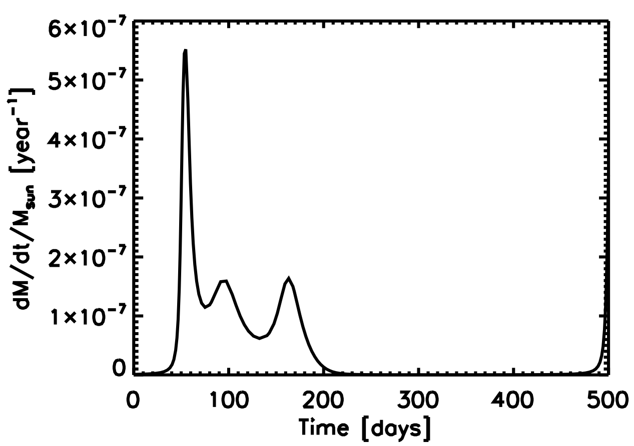
RIAF vs. Thin Disk

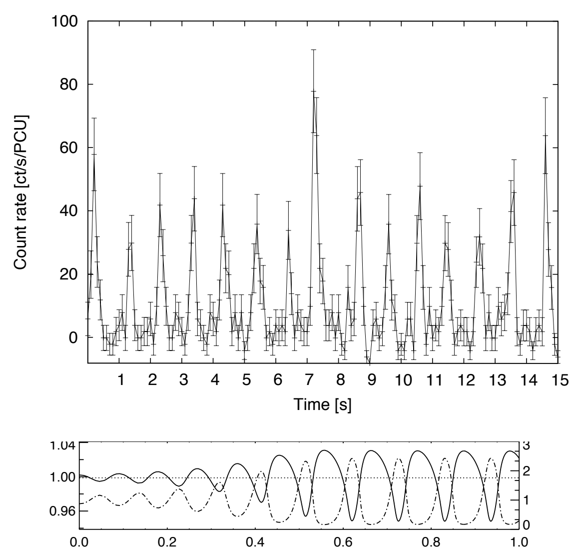
- larger R_{in} than for thin disk (easier for field to 'push back')
- Inhibit field advection (needed to launch jet)
- Stronger outflows (flow barely bound)
- Block pulsations from surface, obscure radio emission in quiescence



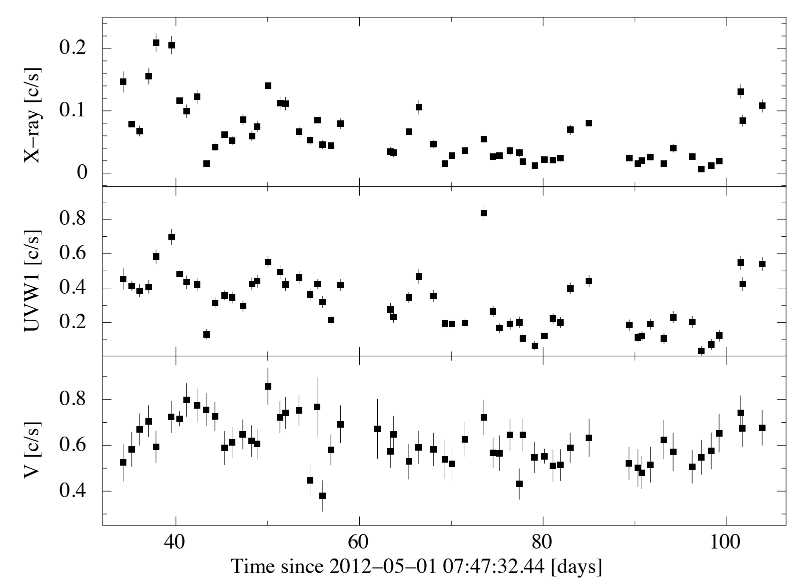
Conclusions

$R_m > R_{corot}$ does not always result in 'propeller' solution: dead discs are possible





Dead discs can produce episodic accretion bursts;
Seen in TTauri star EX Lupi, NGC 6440 X-2, SGR 1808.8-3658



Persistent NS binaries with magnetic fields can impose constraints on RIAF models