



On the nature of Z-sources: neutron star magnetic field, accretion disk structure and evolution

Shuang-Nan ZHANG (张双南)

Key Laboratory of & Center for Particle Astrophysics

Institute of High Energy Physics

Chinese Academy of Sciences

zhangsn@ihep.ac.cn

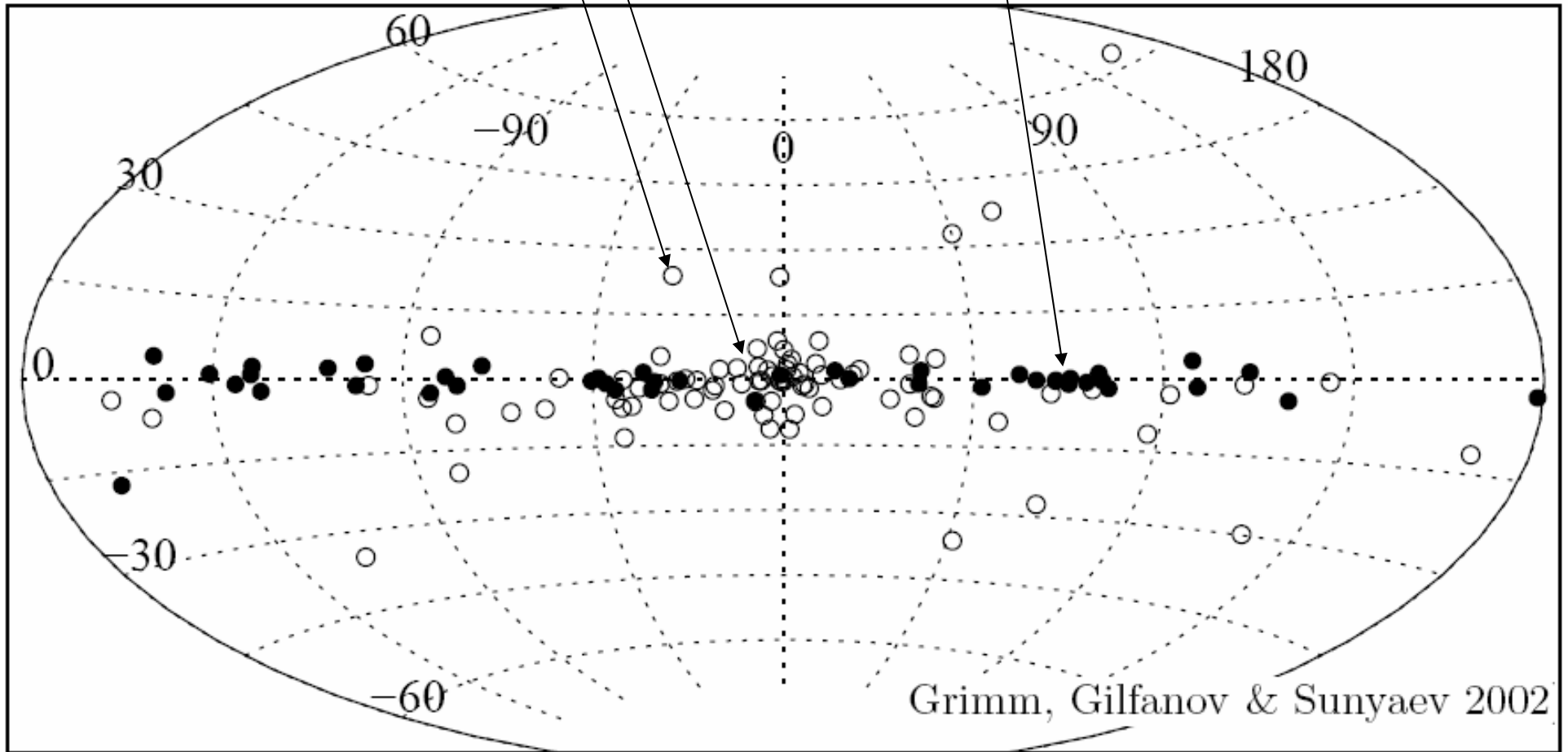
Main author and contributor: Guo-Qiang Ding (丁国强)

Ulumuqi Astronomical Observatory

G. Q. Ding, S. N. Zhang, N. Wang, J. L. Qu, and S. P. Yan

Thanks for **Feng Yuan** for a good question and nice suggestion!

Distributions of Low-Mass and High-Mass X-Ray Binaries



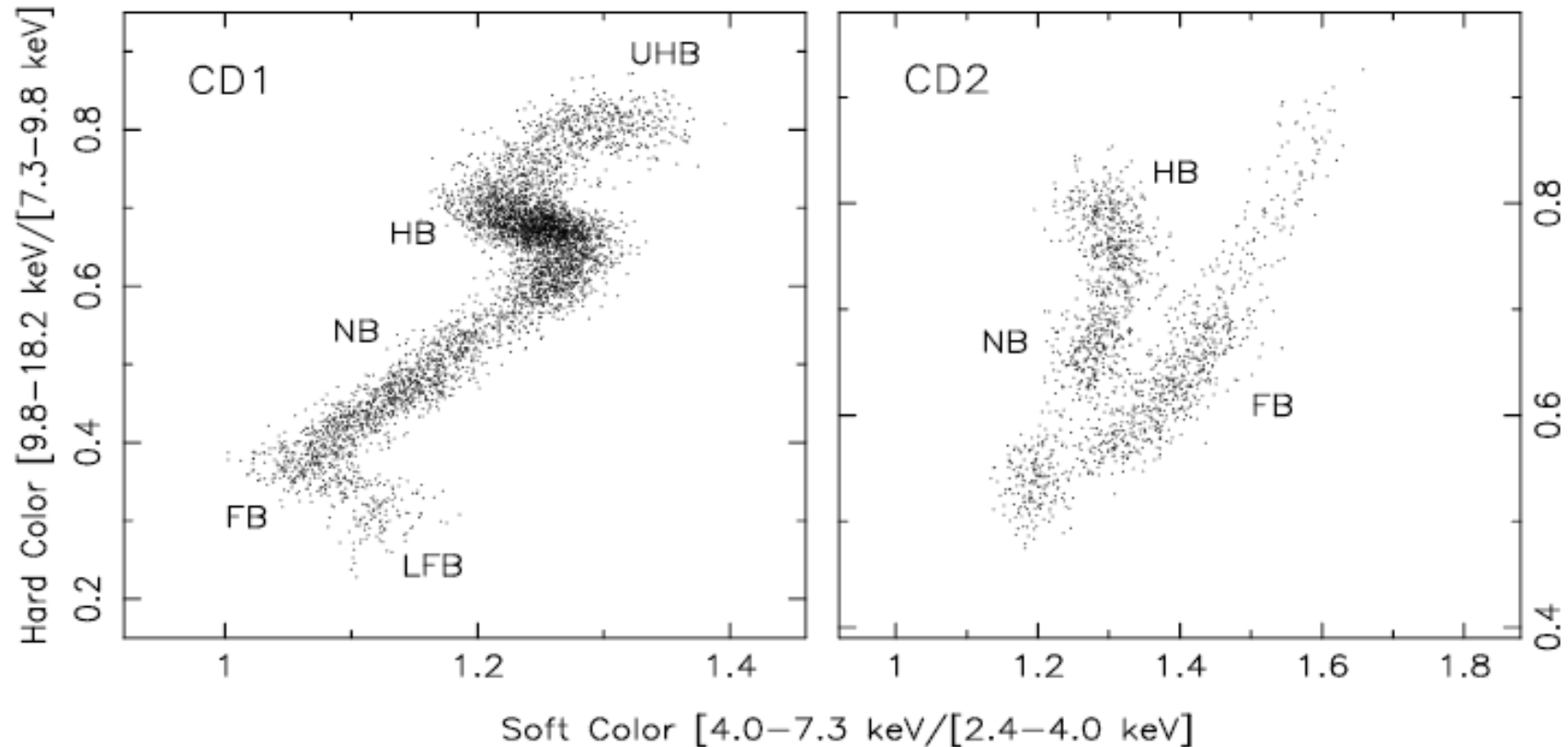
LMXB: old population, in globular clusters and galactic center

HMXB: young population, in the galactic plane

Low-Mass and High-Mass NS X-Ray Binaries

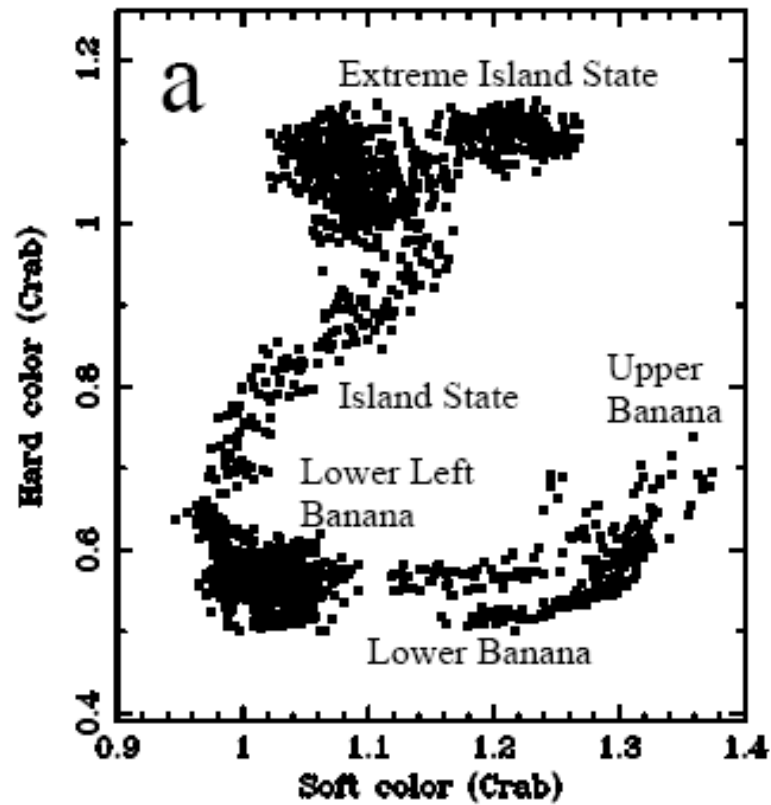
	Low-Mass NS	High-Mass NS
Donor star mass	$< \sim M_{\text{sun}}$	$> 10 M_{\text{sun}}$
Accretion mode	Disk accretion fed by Roche-Lobe overflow	Companion's stellar wind accretion fed
Lifetime	10^7 - 10^9 yr	10^5 - 10^7 yr
NS surface B	$< 10^{11}$ G	$> 10^{11}$ G
Main properties	X-ray bursters (NS) ms X-ray pulsars (NS) Other atoll sources (NS?) Other Z-sources (NS?)	Long period X-ray pulsars (NS)

Color-color diagrams during the bright state of the first transient Z-source XTE J1701-462

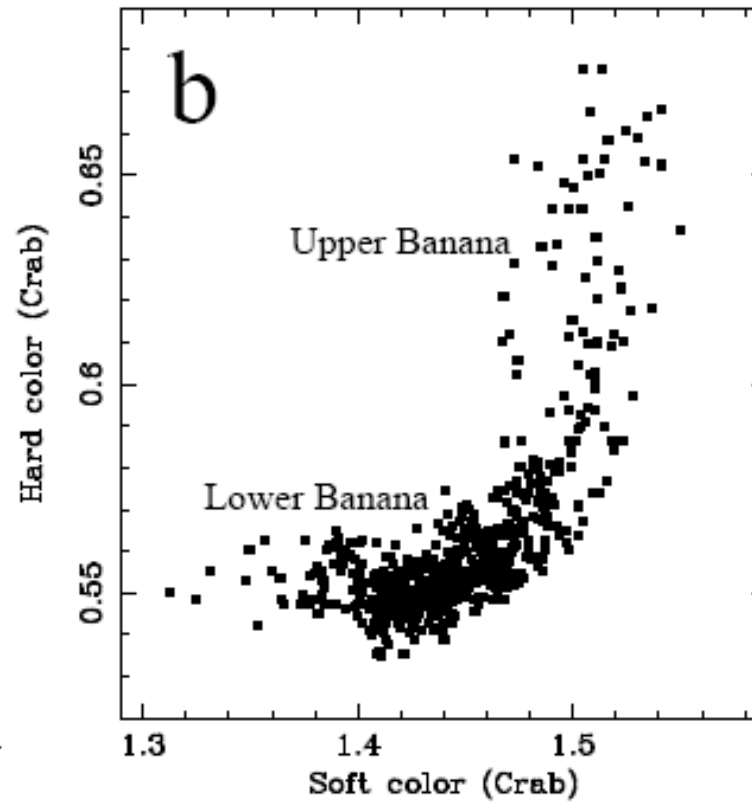


However, XTE J1701-462 is also an atoll-source during its very low luminosity state.

Color-Color Diagrams of two typical atoll-sources



4U1608-52

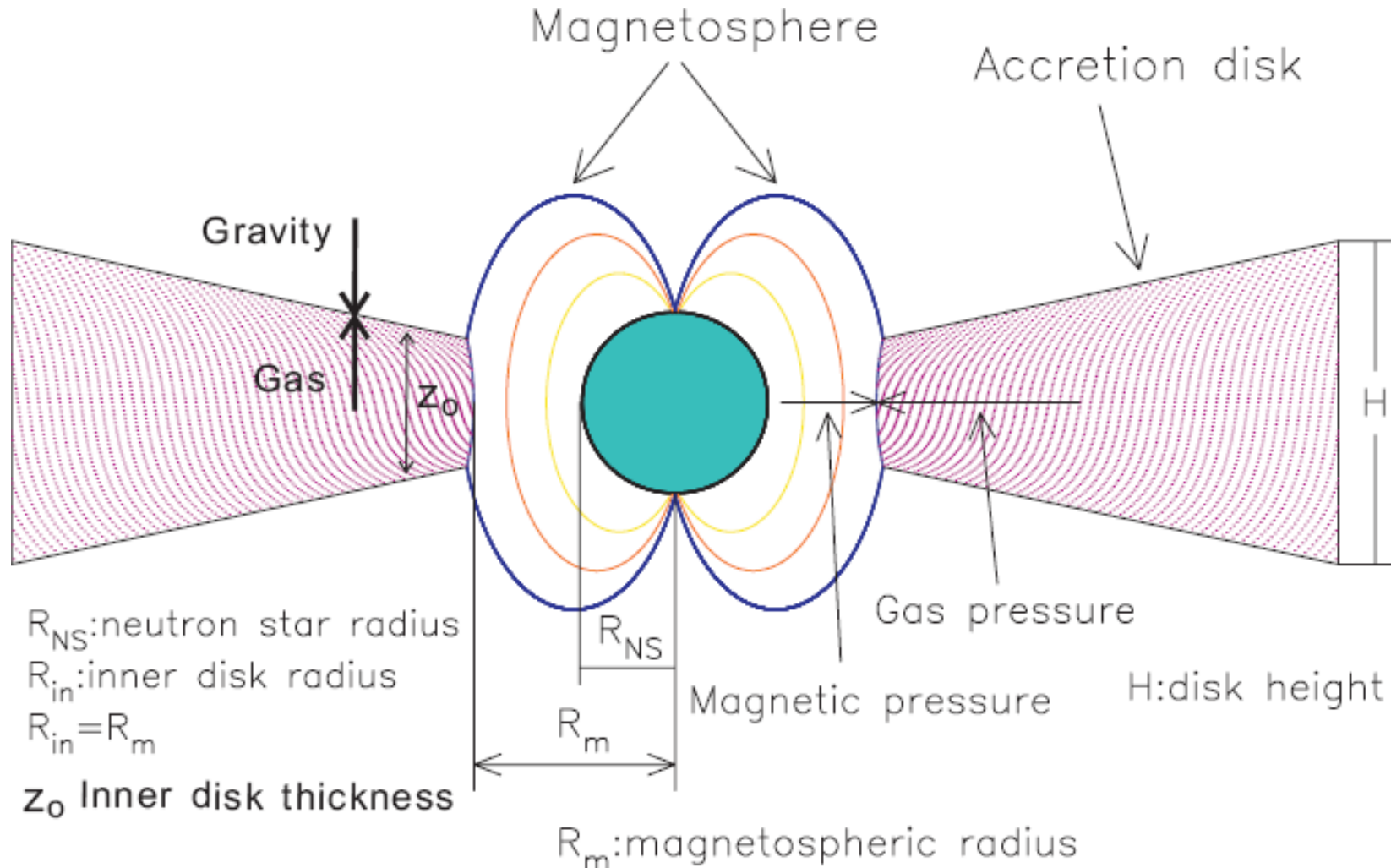


GX9+1

Nature of Z- and atoll-sources?

- All previously known Z-sources are much more luminous than atoll-sources on average.
 - Does disk accretion rate distinguish between Z- and atoll sources?
 - And if so, why?
- However the peak luminosity of transient atoll-sources can be higher than Z-sources at less luminous state.
 - A second parameter is involved. Is NS magnetic field of Z-sources higher than that of atoll-sources?
 - But NS magnetic field is difficult to measure.
- For non-bursting and non-pulsating sources, any evidence for NS?

Gas pressure dominated disk-magnetosphere model



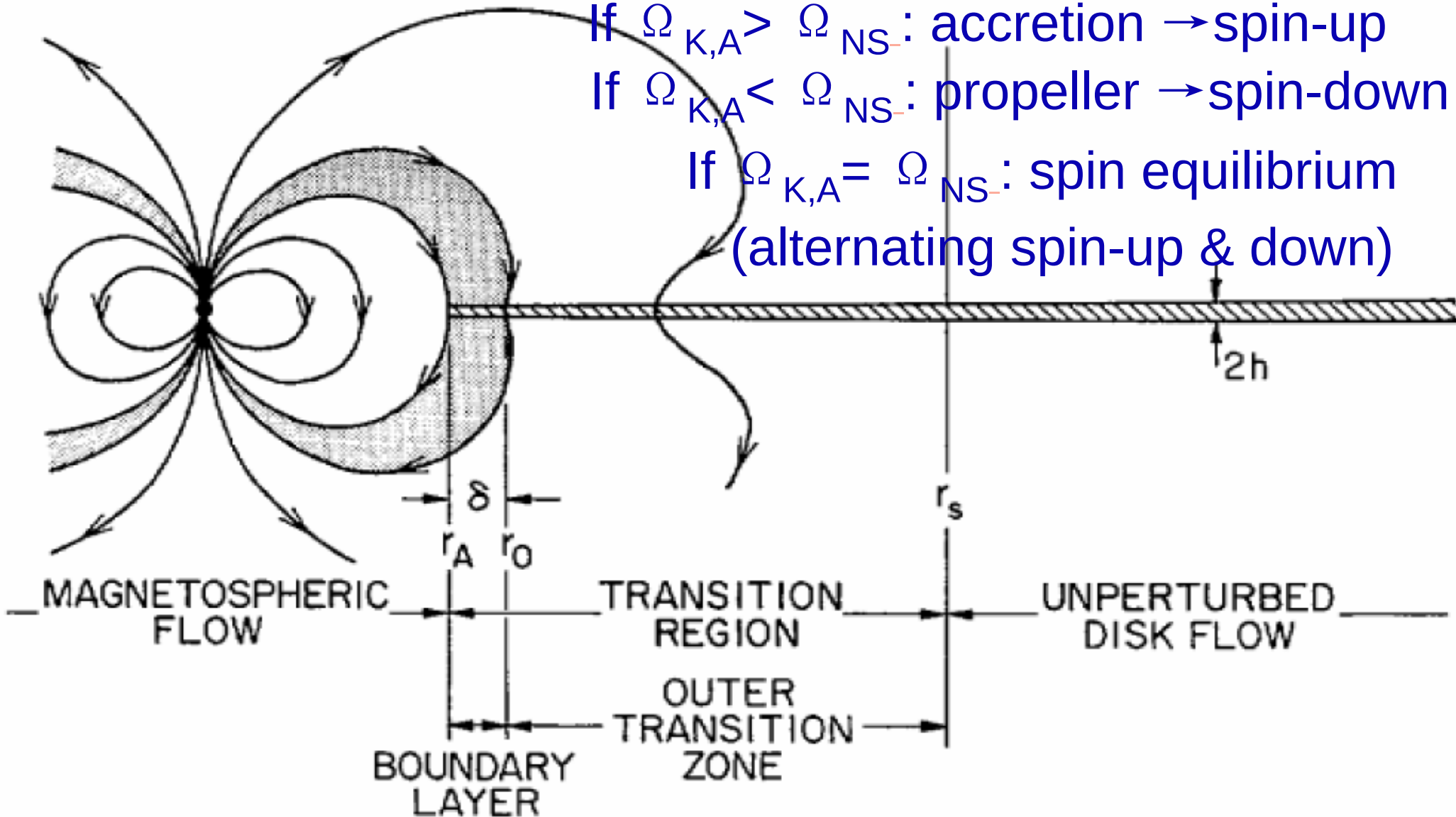
$$R_{in} = R_m \propto B^{4/5} \dot{M}^{-2/5} \propto \dot{M}^{-2/5}$$

Signature of NS magnetosphere, but never observed!

Accreting Neutron Stars

$$R_{in} = R_A \propto B^{4/5} \dot{M}^{-2/5} \propto \dot{M}^{-2/5}$$

If $\Omega_{K,A} > \Omega_{NS}$: accretion $\rightarrow$ spin-up
 If $\Omega_{K,A} < \Omega_{NS}$: propeller $\rightarrow$ spin-down
 If $\Omega_{K,A} = \Omega_{NS}$: spin equilibrium
 (alternating spin-up & down)



Propeller effect as evidence for NS magnetosphere?

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SPECTRAL STATE TRANSITIONS IN AQUILA X-1: EVIDENCE FOR “PROPELLER” EFFECTS

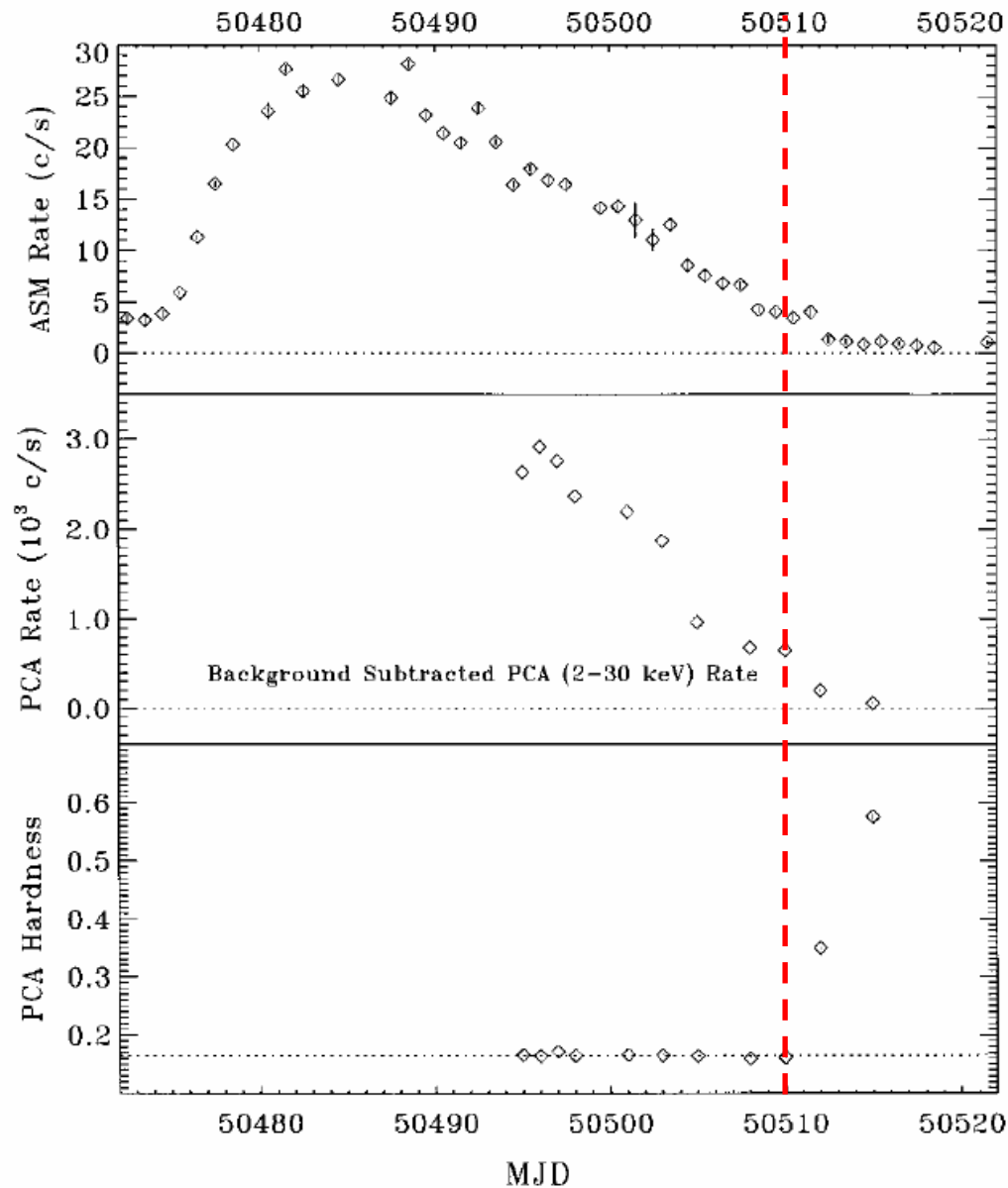
S. N. ZHANG,^{1,2} W. YU,^{1,3} AND W. ZHANG⁴

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ABSTRACT

Aquila X-1 is a soft X-ray transient source and emits type I X-ray bursts. A spectral state transition was observed with *RXTE* during its outburst decay in 1997 February and March. Its 10–30 keV and 5–10 keV count rate ratio increased suddenly when its luminosity was between 4 and 12×10^{35} ergs s⁻¹, assuming a 2.5 kpc distance. Spectral fitting with a model composed of a blackbody and a power-law component showed that its blackbody component decreased and that the power-law component became much harder significantly and simultaneously. We interpret this transition to be caused by the centrifugal barrier, more commonly known as the “propeller” effect. We thus infer that the magnetic field strength of the neutron star is around 1×10^8 G, if the neutron star spin period is 1.8 ms. Similarly, we infer the neutron star magnetic field strength in another soft X-ray transient Cen X-4 is about 2×10^9 G. We also propose a unified scheme for spectral state transitions in soft X-ray transients, from soft high state to hard low state and further to quiescent state. With this scheme accretion onto neutron star may take place even during the propeller regime.

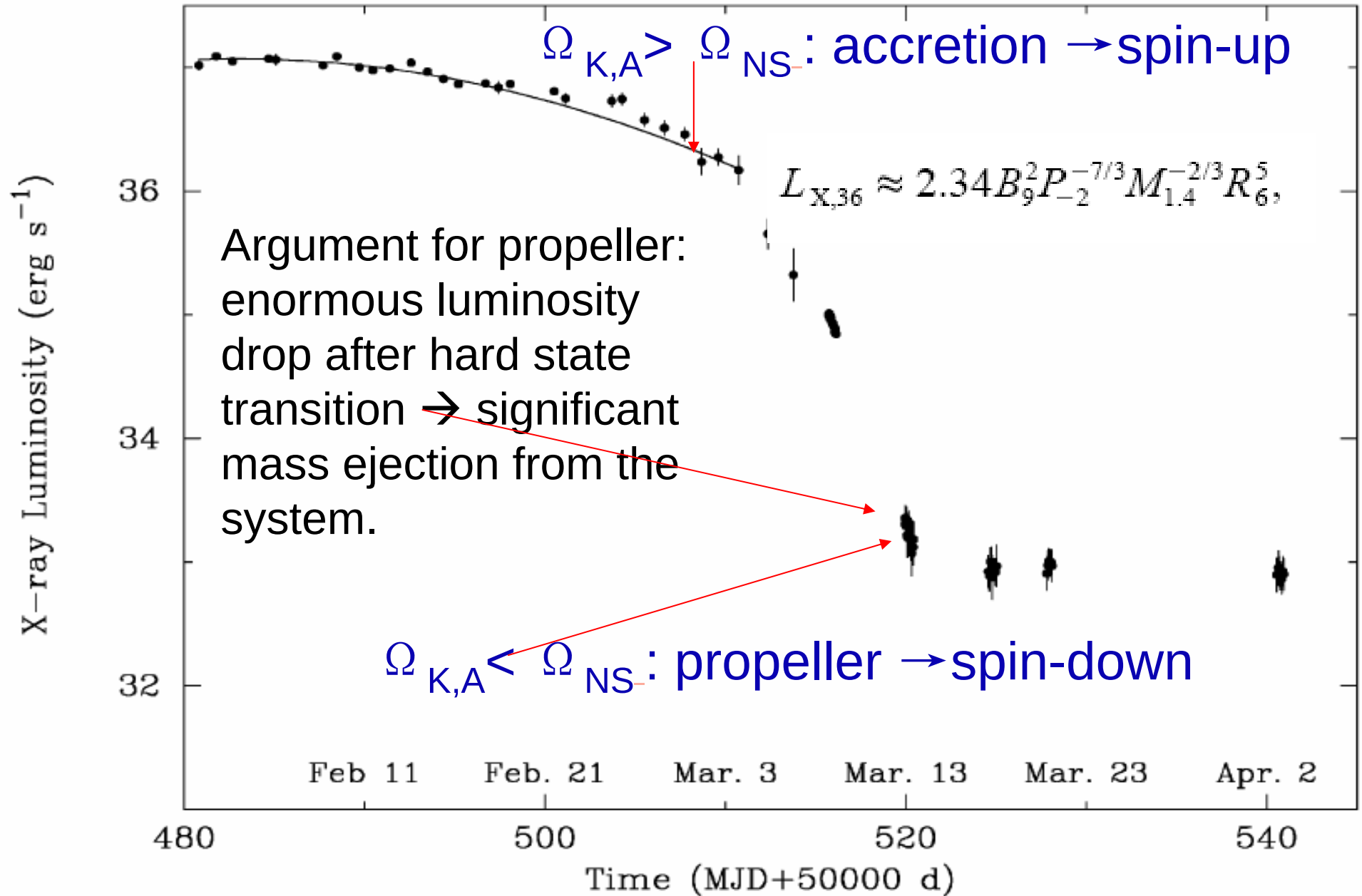
Hard state transition interpreted as onset of propeller state

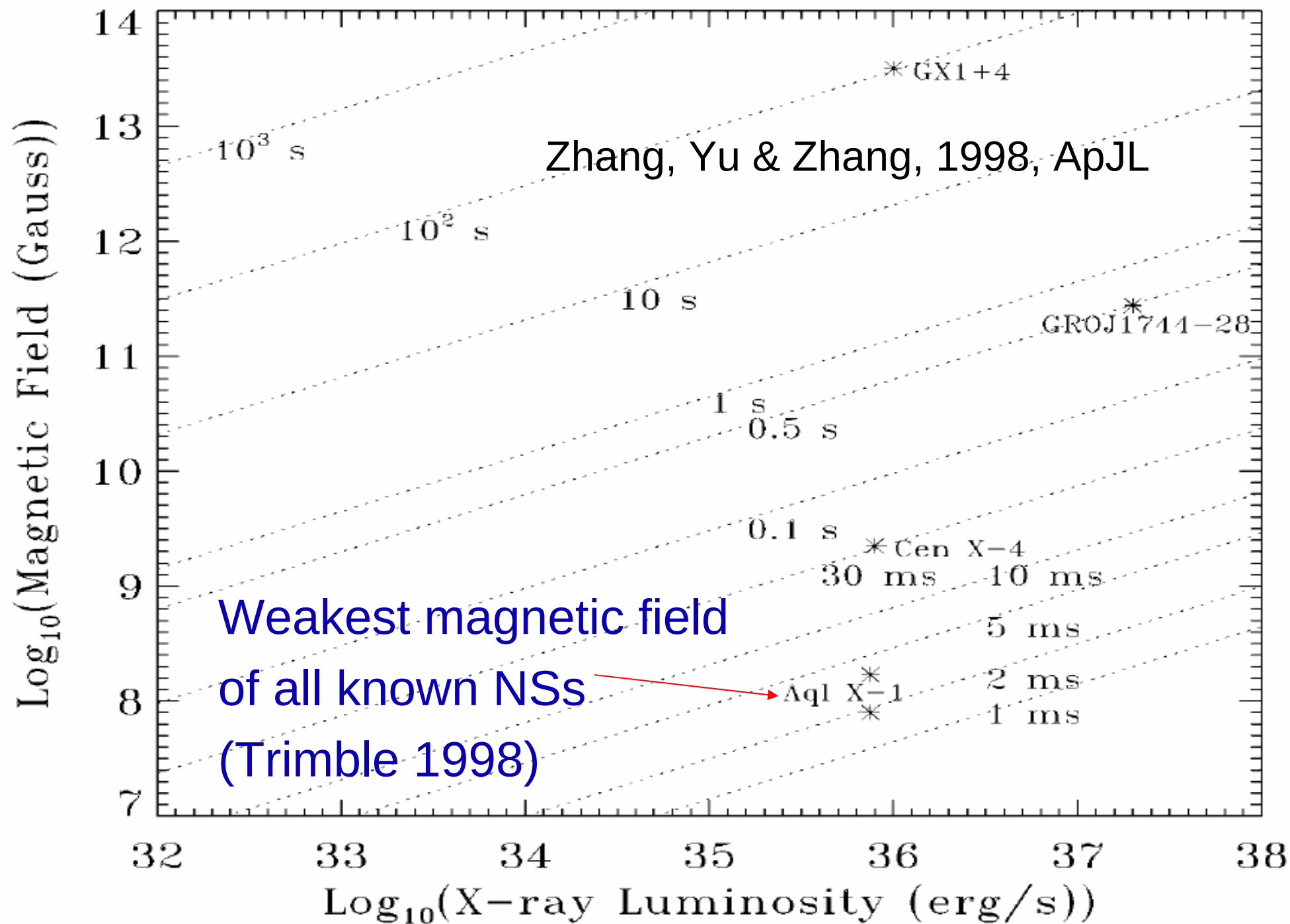


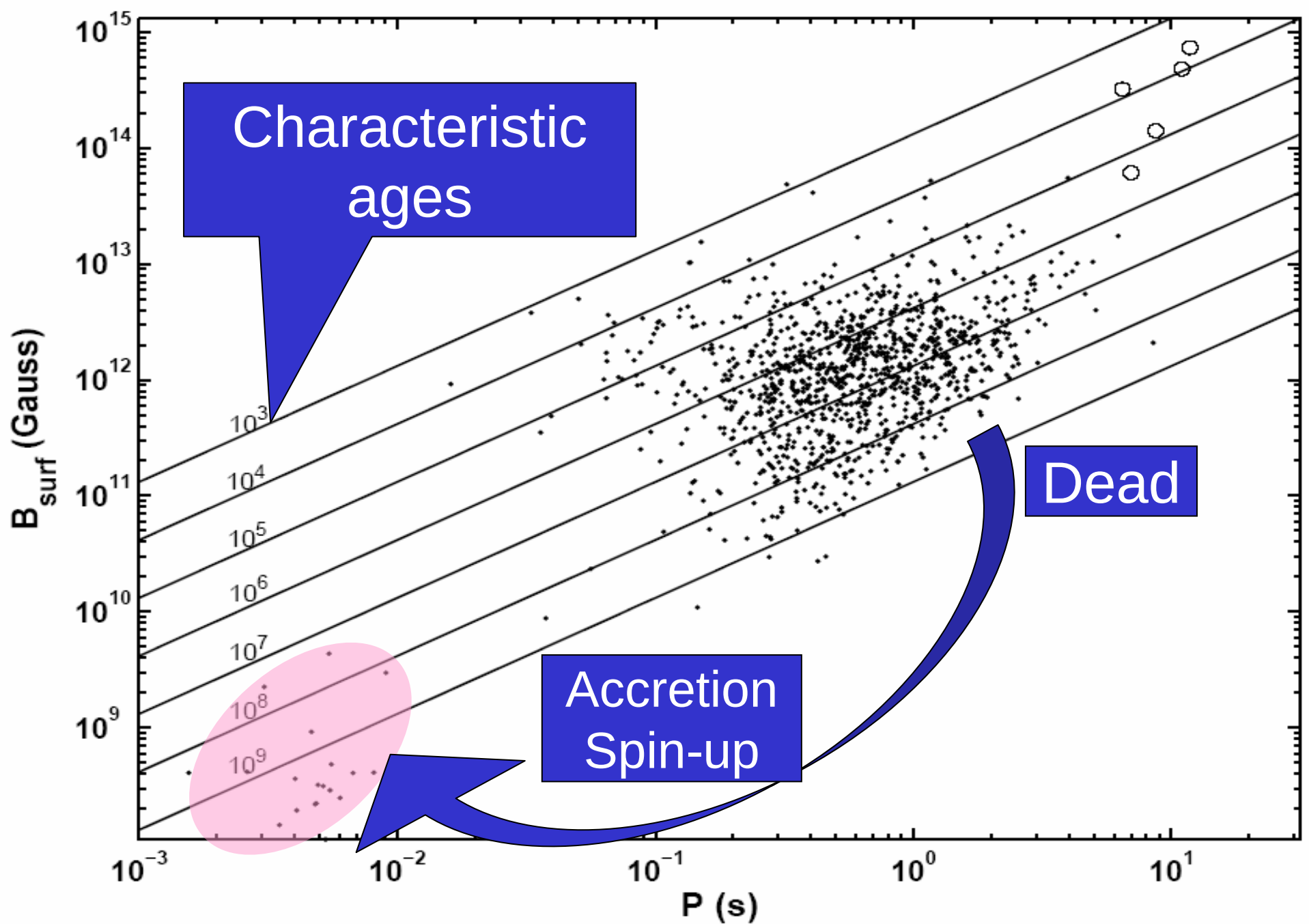
Zhang, Yu & Zhang,
1998, ApJL

$$L_{X,36} \approx 2.34 B_9^2 P_{-2}^{-7/3} M_{1.4}^{-2/3} R_6^5,$$

Aql X-1
Light Curve of Feb. 1997 outburst







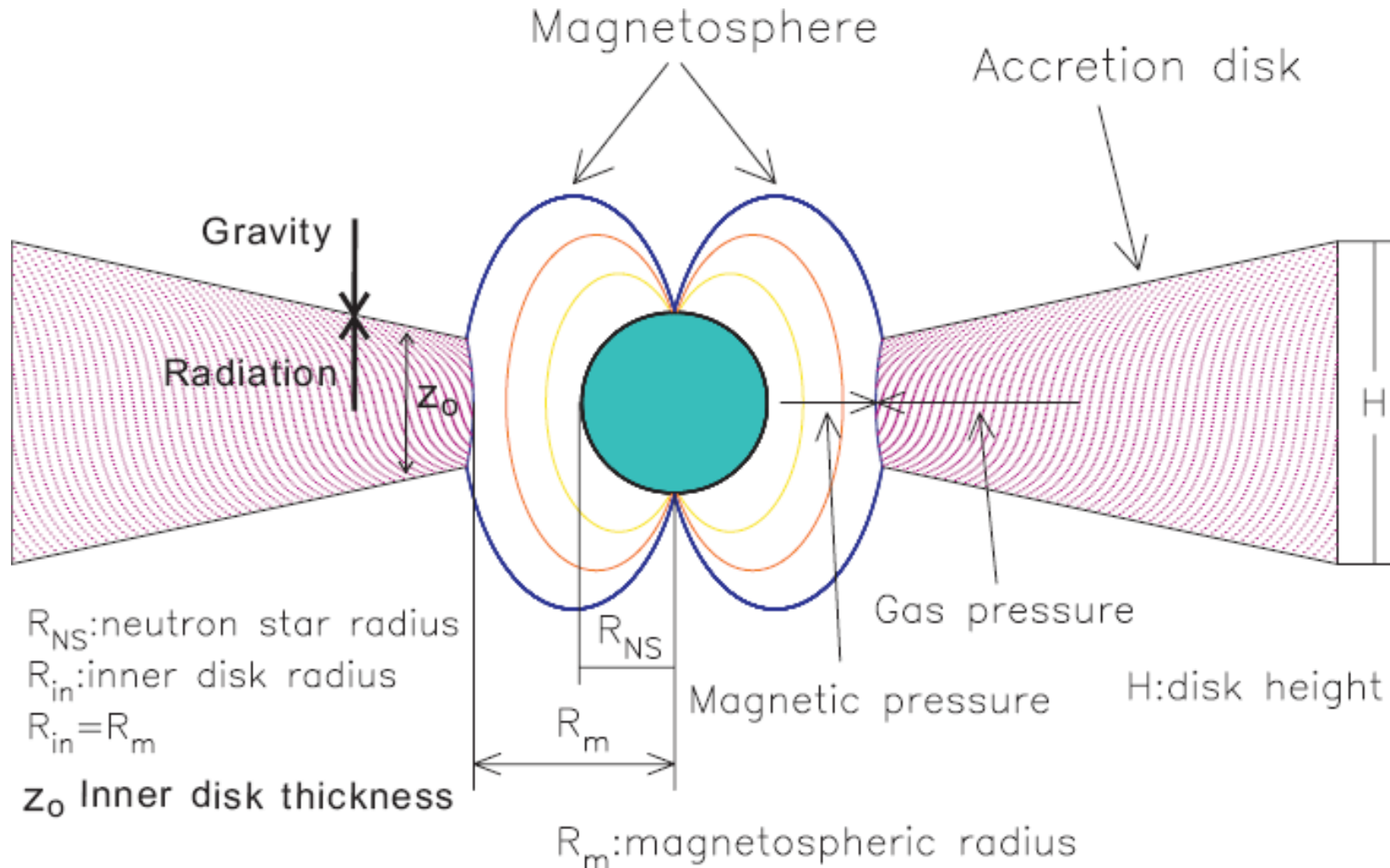
ADAF in quiescent NS SXT and ms pulsars

quiescent state are very natural. We emphasize that the major difference between our model and the previous ones is that *in the quiescent state of our model, the optically thick disk is truncated, due to the advection dominance, very far away from the light cylinder of the neutron star magnetosphere. Thus, near-spherical accretion onto the neutron star poles are possible. We predict that some SXTs in quiescence should be millisecond X-ray pulsars.*

Confirmed by discoveries of ms X-ray pulsars in SXTs!

Zhang, Yu & Zhang, 1998, ApJL

Radiation pressure dominated disk-magnetosphere model



Radiation pressure dominates over gas pressure @ $> \sim 0.3$ Edd
Most Z-sources spend most of their lives $\sim$ Edd

Expected correlations of radiation pressure dominated disk

$$R_{in} = R_m \propto B_a^{4/5} \dot{M}^{-2/5}, B_a = B_0 \sqrt{\xi v_r / v_{ff}}, z_0 = \xi R_{in}$$

Without knowing the disk structure *a priori*, i.e., ξ, v_r, v_{ff} , only B_a , can be inferred from observations (with disk-BB model) directly.

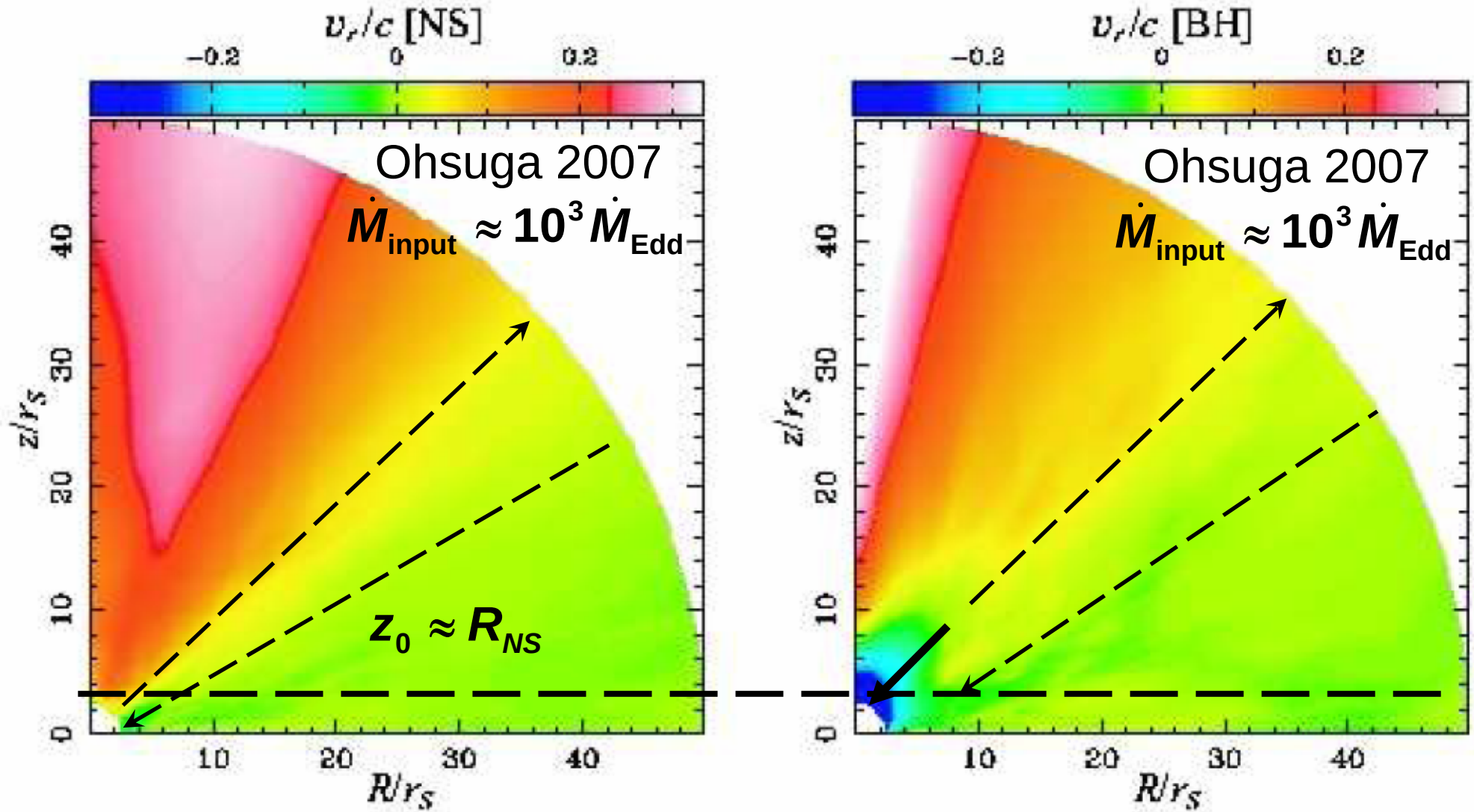
If no disk structure evolution,

$$\sqrt{\xi v_r / v_{ff}} = \text{constant} \rightarrow B_a \propto B_0 \rightarrow R_{in} \propto \dot{M}^{-2/5} \quad \text{but never observed!}$$

Shakura & Sunyaev (1973): in a radiation pressure dominated disk, $\xi(\text{in} + \text{out}) \propto \dot{M} \Rightarrow \rho = \text{constant}$. Considering radiation driven outflows, the inflowing disk's thickness $z_0(\text{in}) \approx R_{NS}$

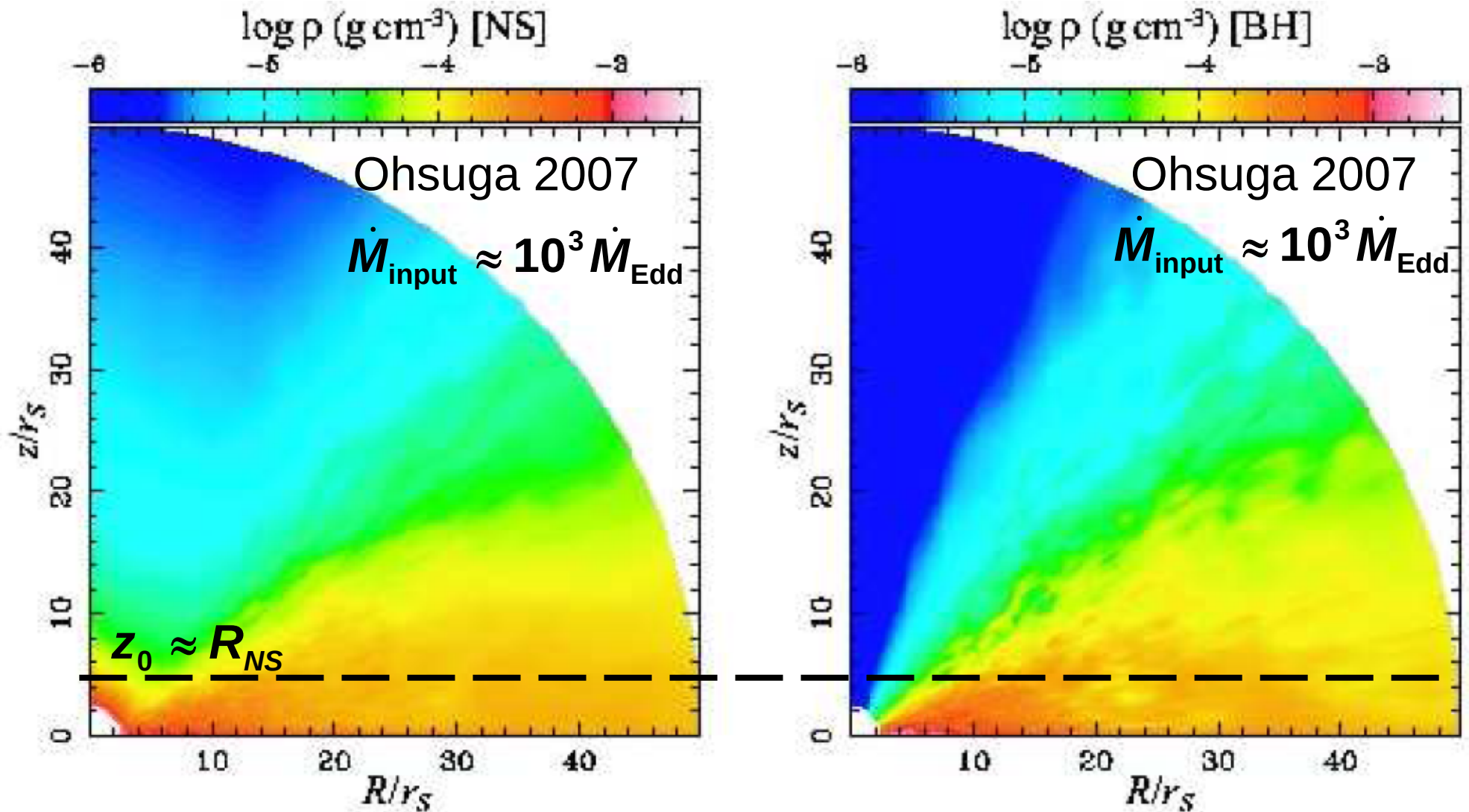
$$\xi \propto \dot{M} \propto v_r / v_{ff} \rightarrow B_a \propto \dot{M} \rightarrow R_{in} \propto \dot{M}^{-2/5} B_a^{4/5} \propto \dot{M}^{2/5}$$

Numerical simulation of supercritical accretion onto NS

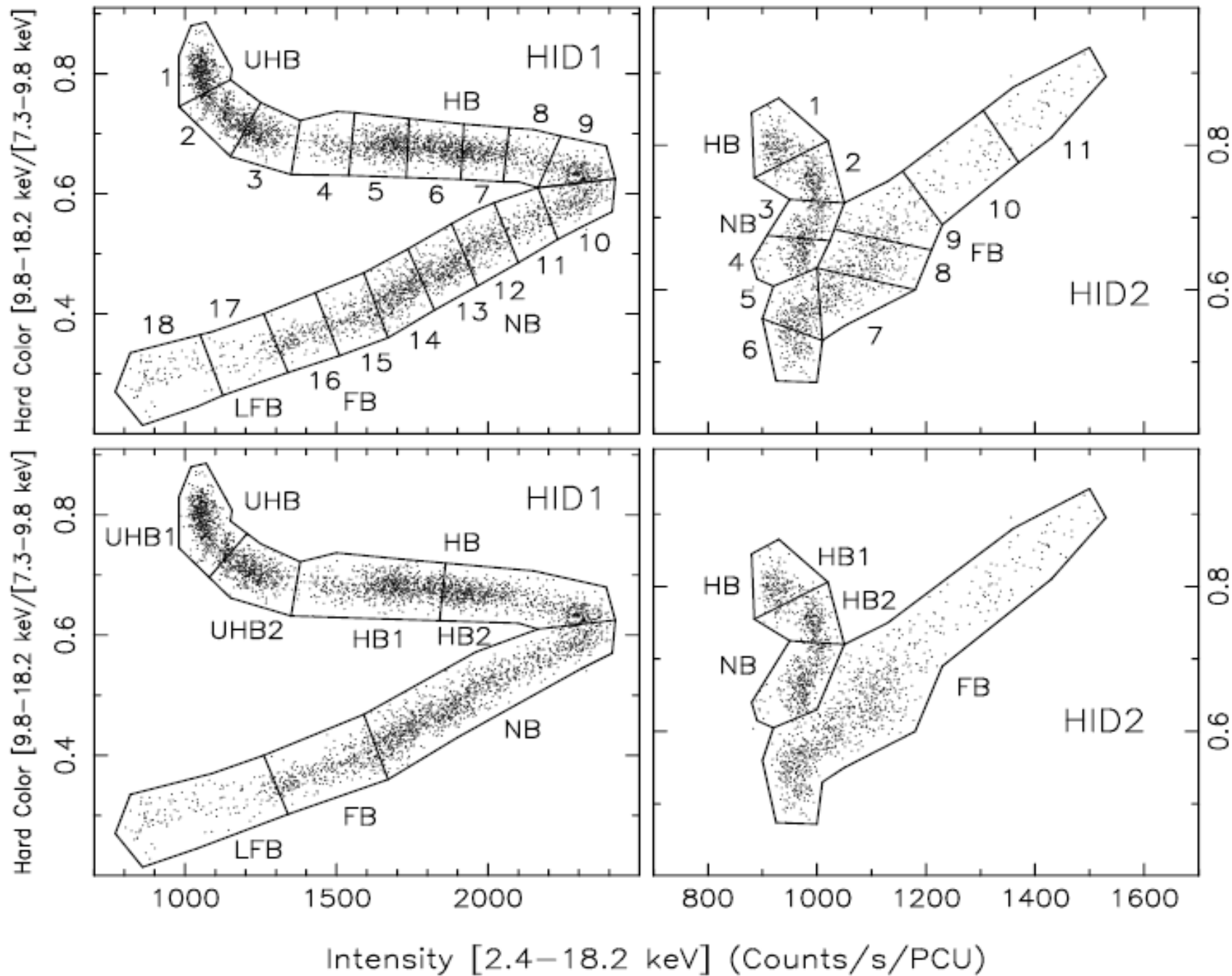


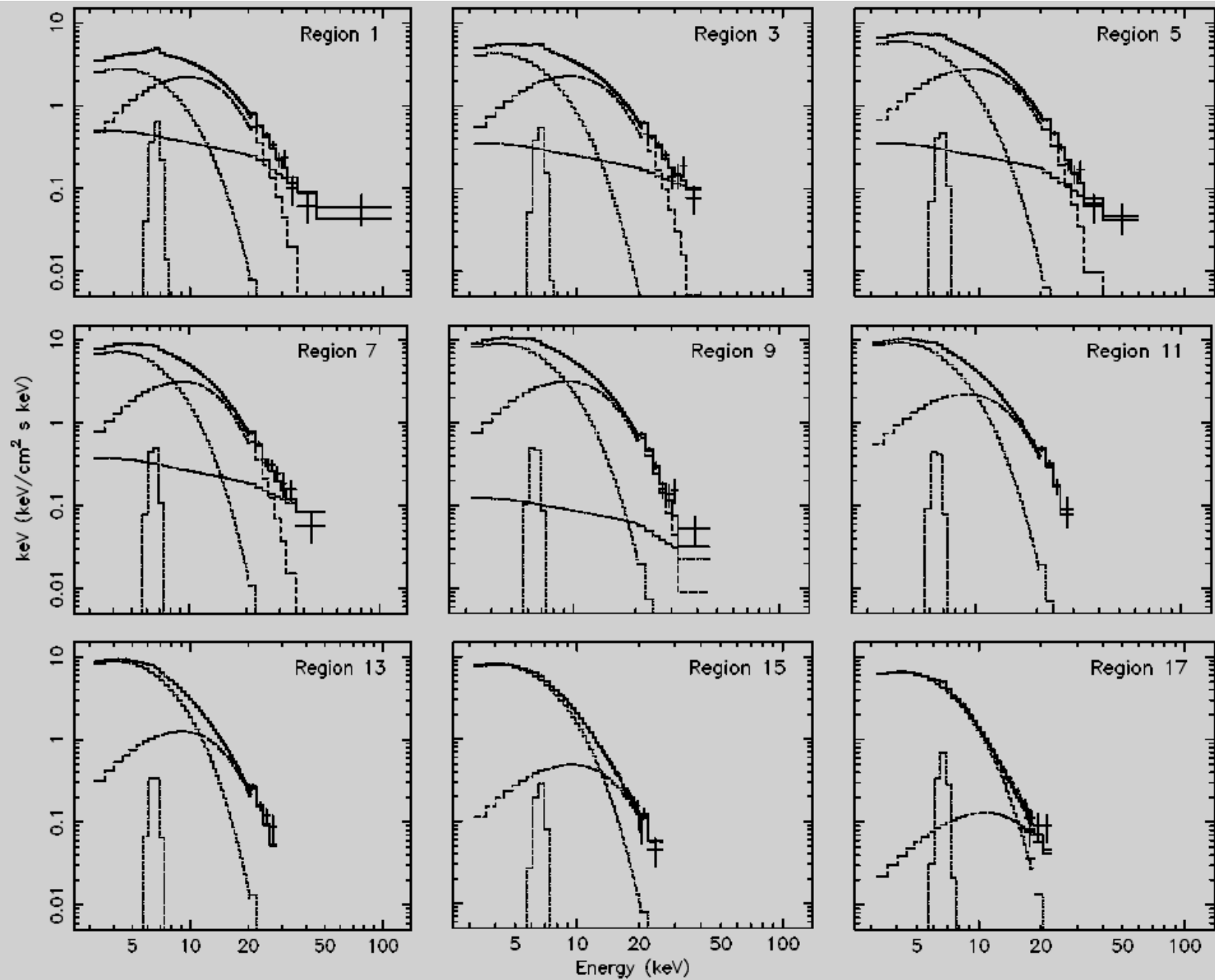
Stronger outflows for NS supercritical accretion

Numerical simulation of supercritical accretion onto NS



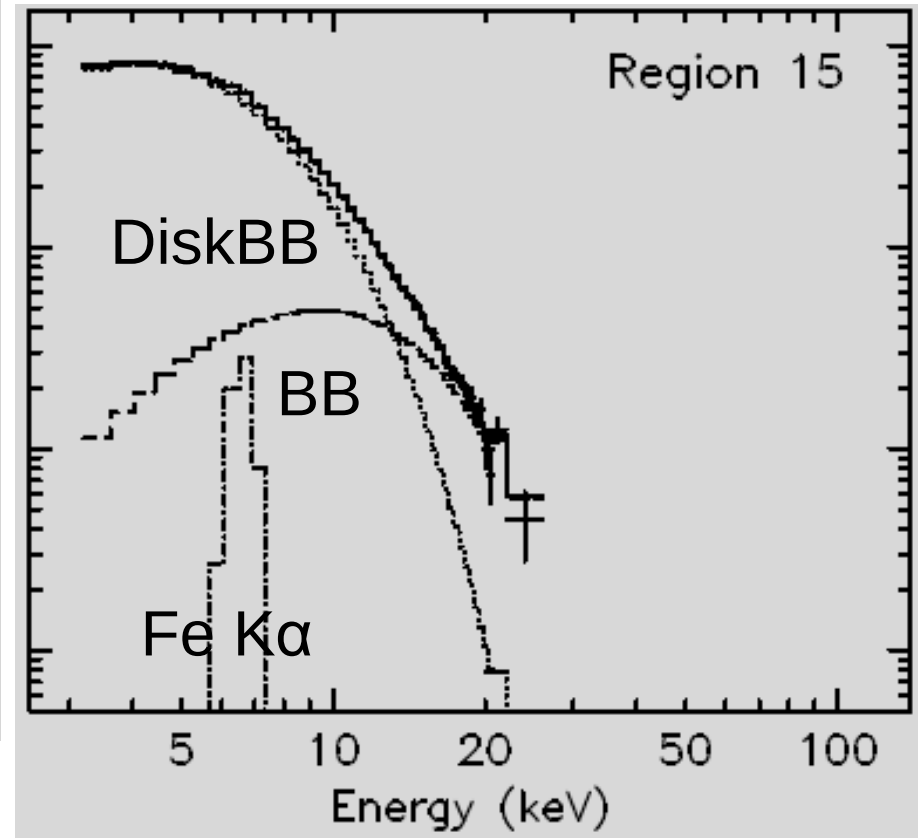
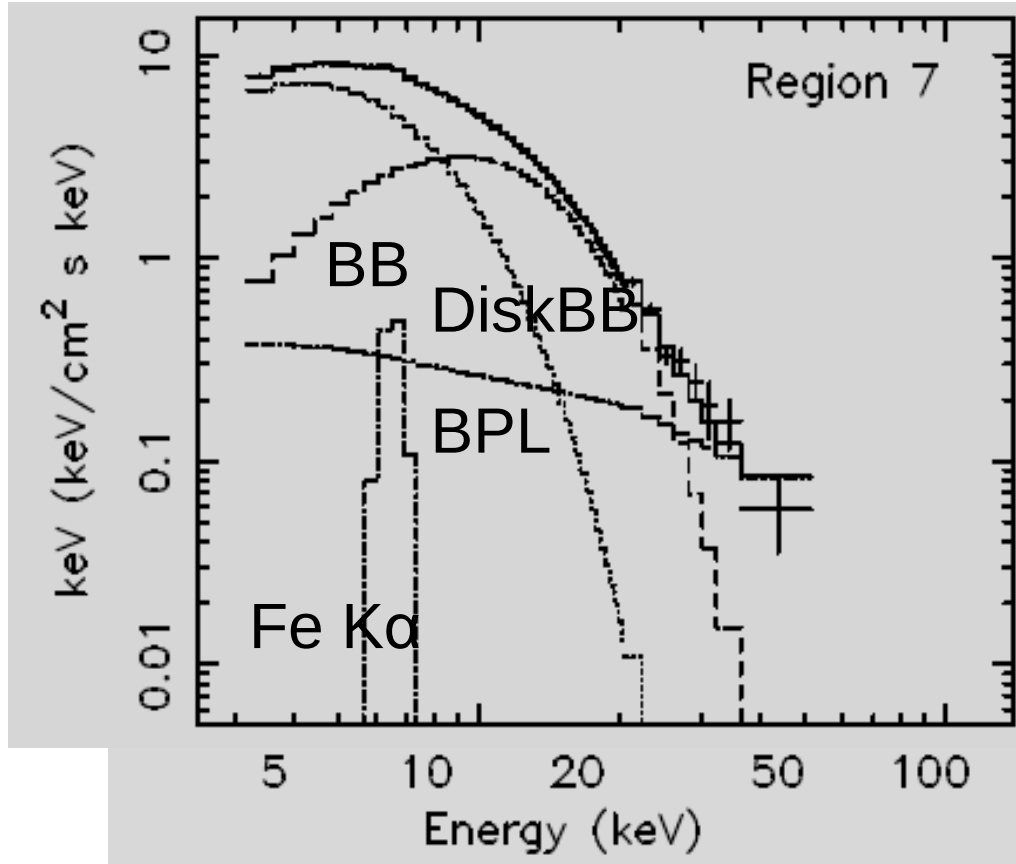
Similar disk but with an accretion shell for NS supercritical accretion



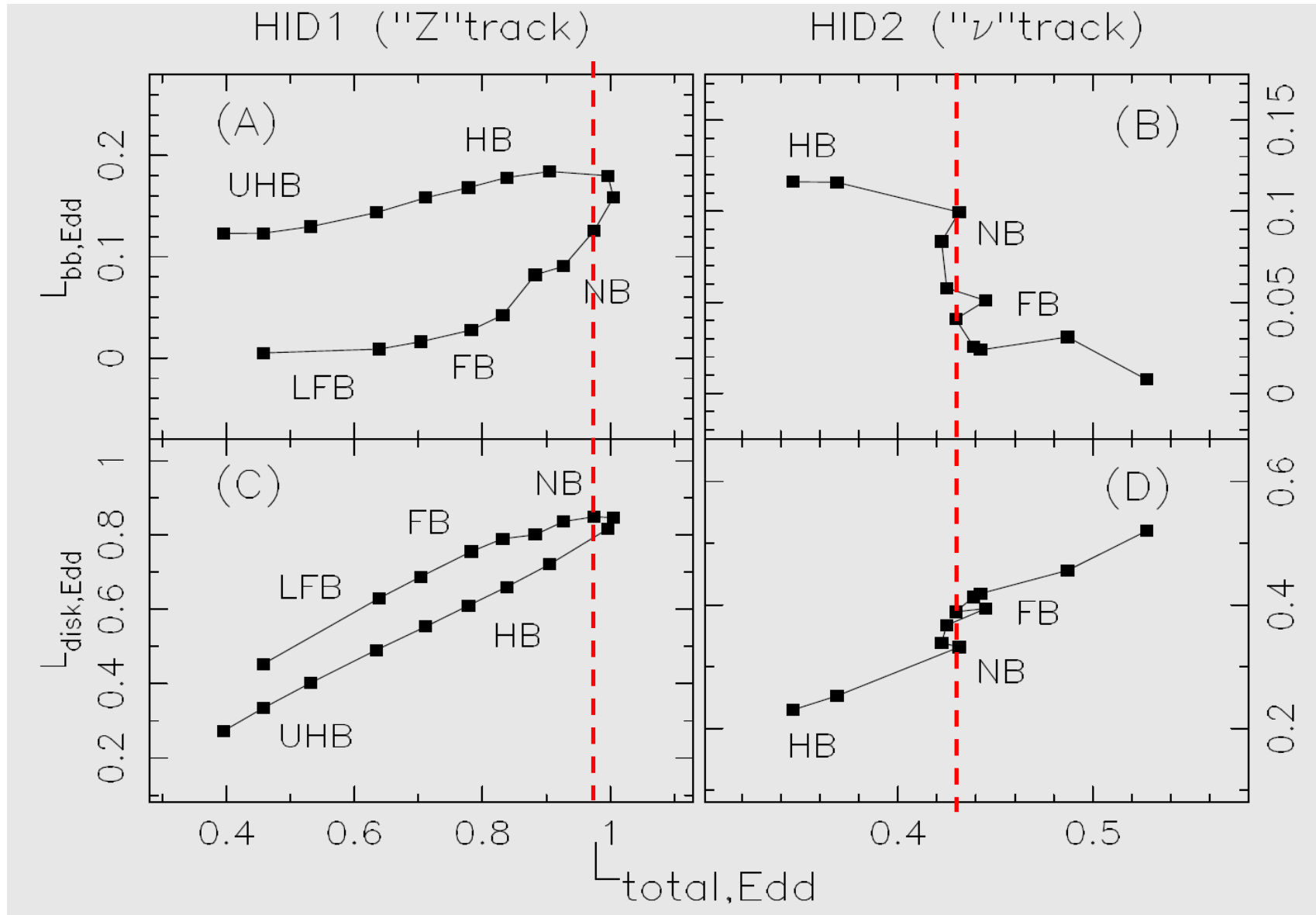


Spectral model

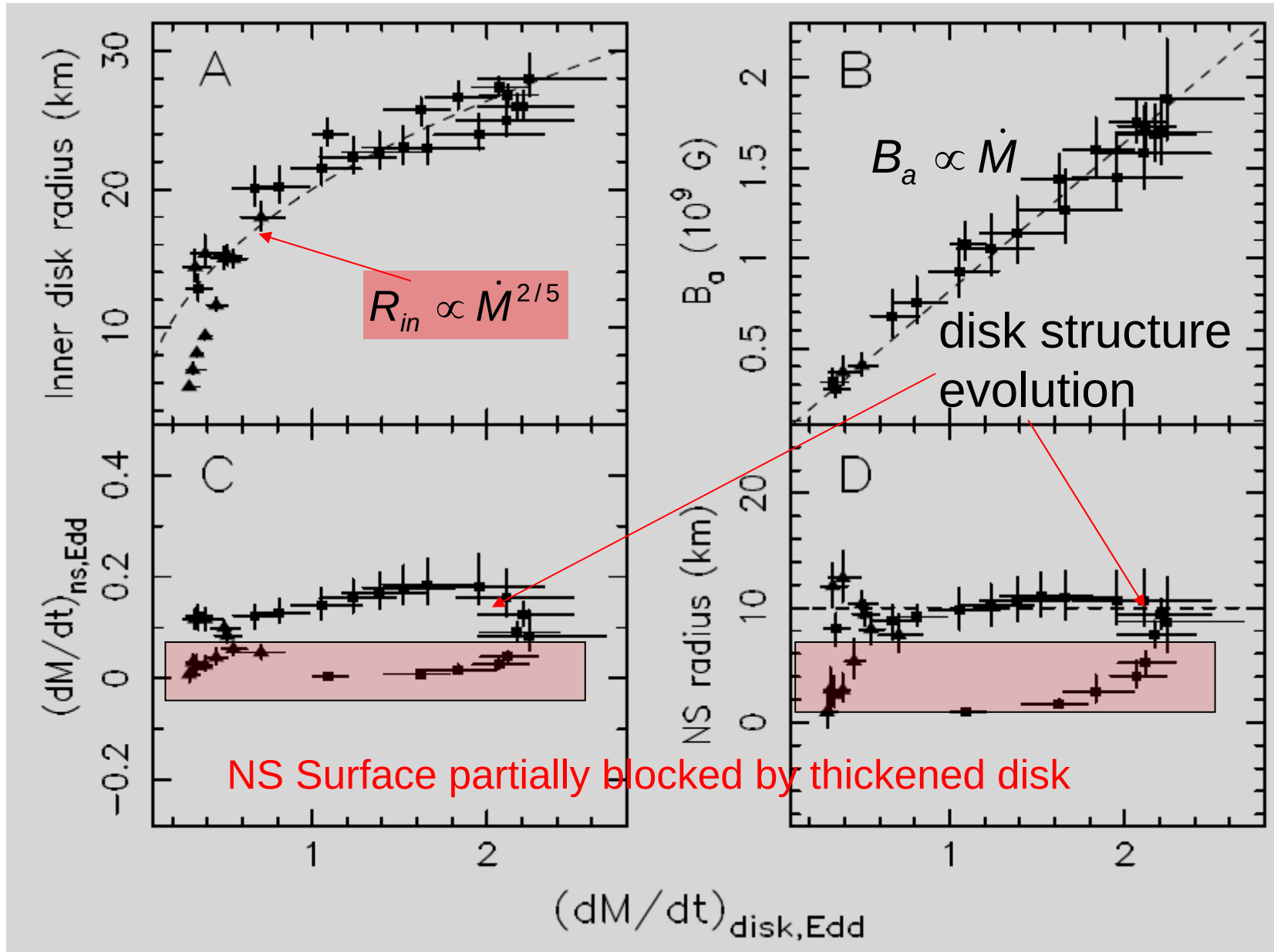
DiskBB (accretion disk) + BB (NS surface) + Fe K α



Bifurcation of total luminosity



Thick disk + magnetosphere model



Measure the surface magnetic field of the NS

At super-Edd, inner disk is spherized (the accretion shell), thus

$$\xi = 1$$

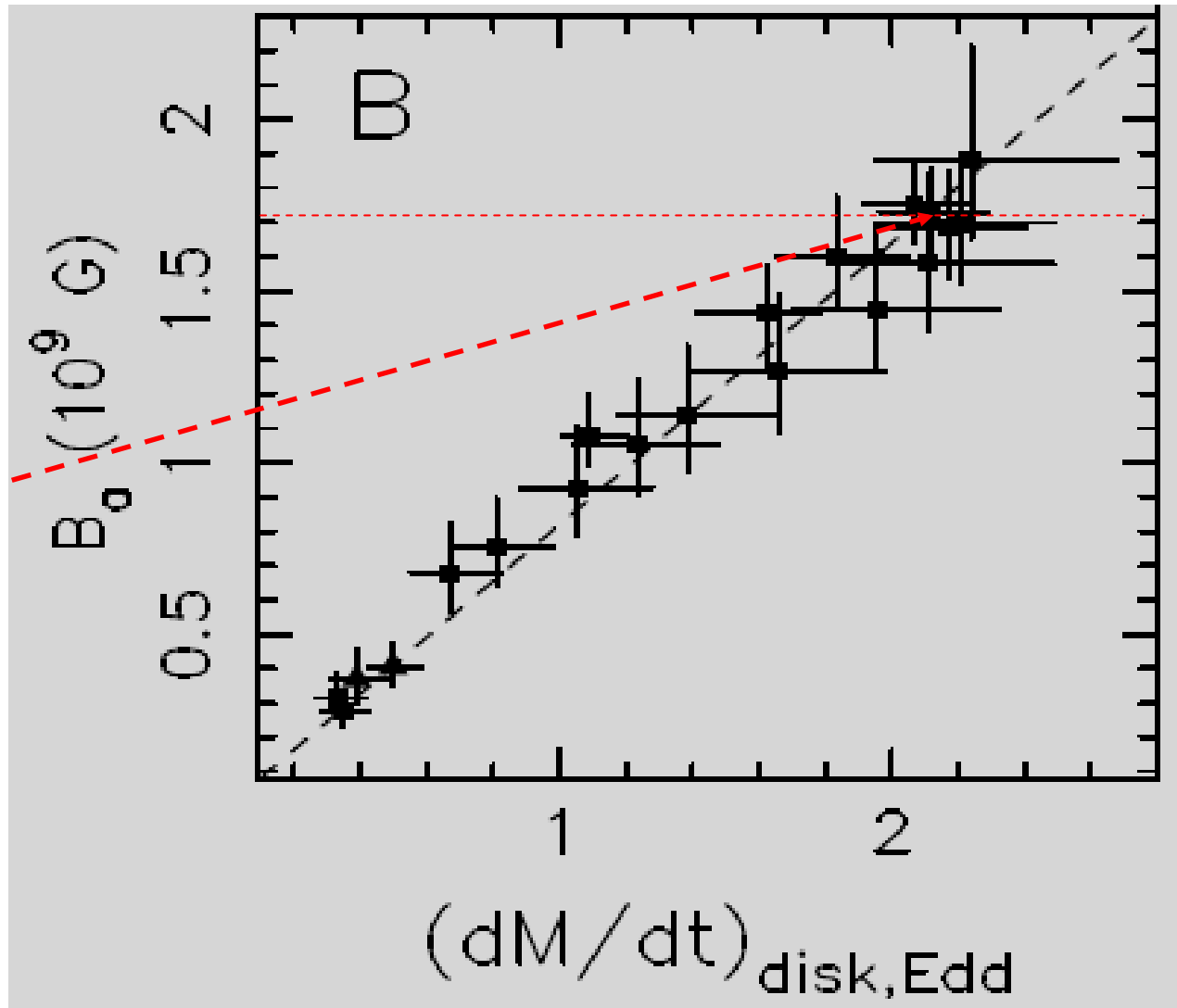
$$0.5 < \mathbf{v}_r / \mathbf{v}_{ff} < 1$$

$$\mathbf{B}_a = \mathbf{B}_0 \sqrt{\xi \mathbf{v}_r / \mathbf{v}_{ff}}$$

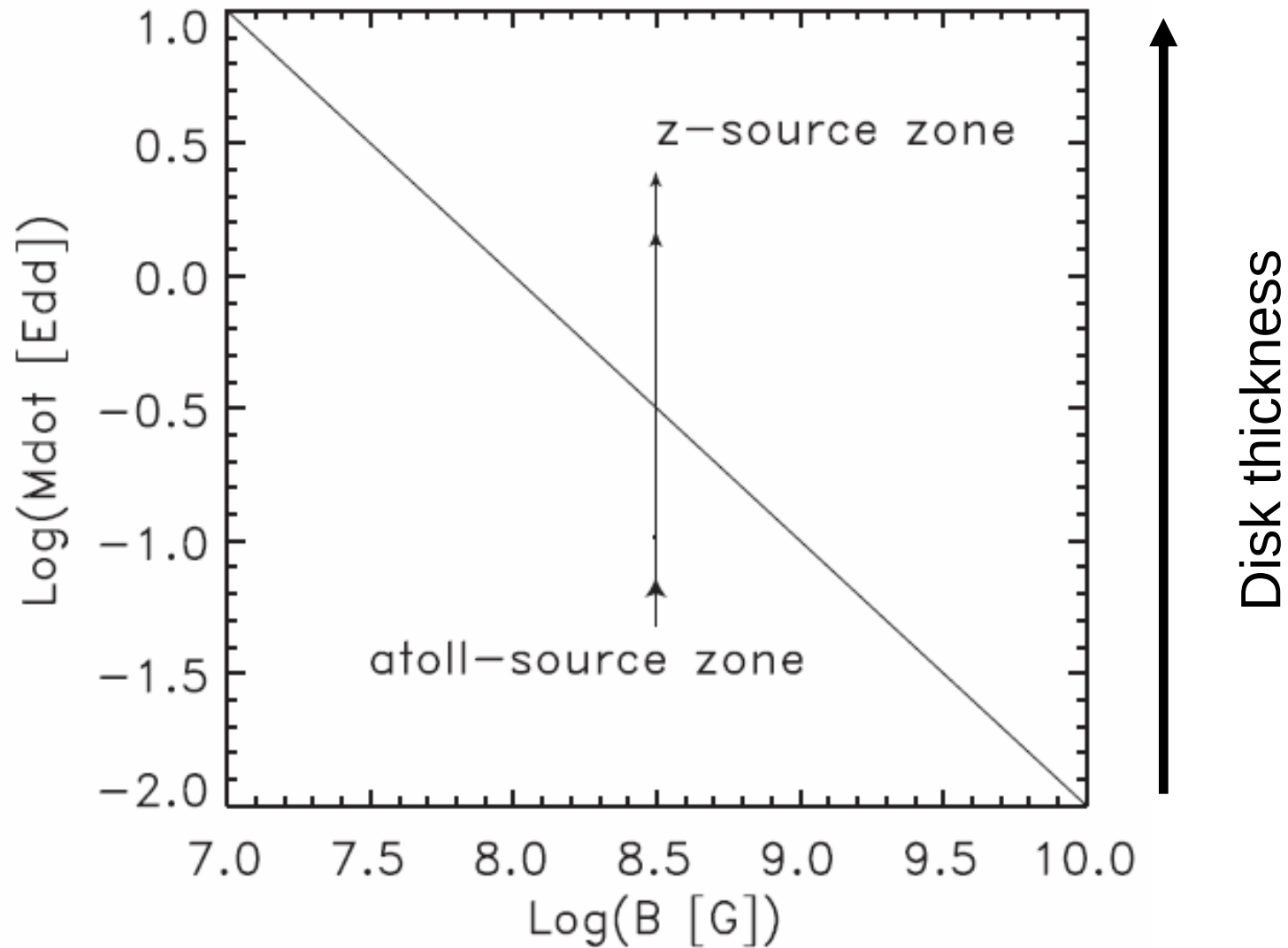
$$= 1.7 \times 10^9 \text{ G}$$

$$\mathbf{B}_0 = [1.7, 2.4] \times 10^9 \text{ G}$$

Unambiguous
evidence for NS
magnetosphere!



Nature of Z- and atoll-sources: two parameter model



Black holes cannot do this!

Conclusions

- For a radiation pressure dominated accretion disk

$$\xi \propto \dot{M} \propto \mathbf{v}_r / \mathbf{v}_{ff} \rightarrow \mathbf{B}_a \propto \dot{M} \rightarrow \mathbf{R}_{in} \propto \dot{M}^{-2/5} \mathbf{B}_a^{4/5} \propto \dot{M}^{2/5}$$

- This evolution produces the Z-track. This phenomenon is not expected and never observed in a BH system, because a BH has no hair!

$$\mathbf{B}_0 = (1.7 - 2.4) \times 10^9 \text{ G for XTE J1701- 462}$$

– Unambiguous evidence for NS magnetosphere!