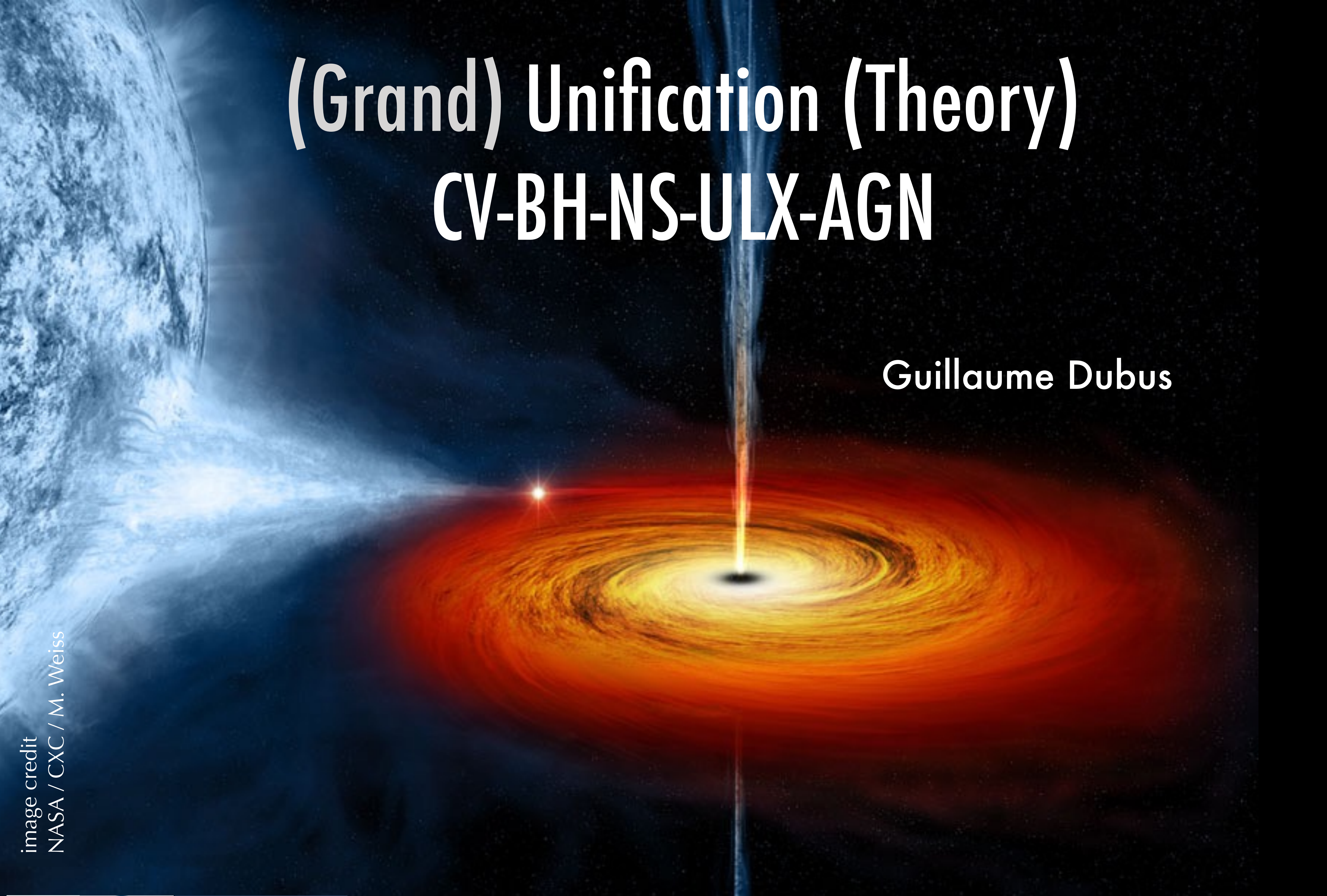


image credit
NASA / CXC / M. Weiss

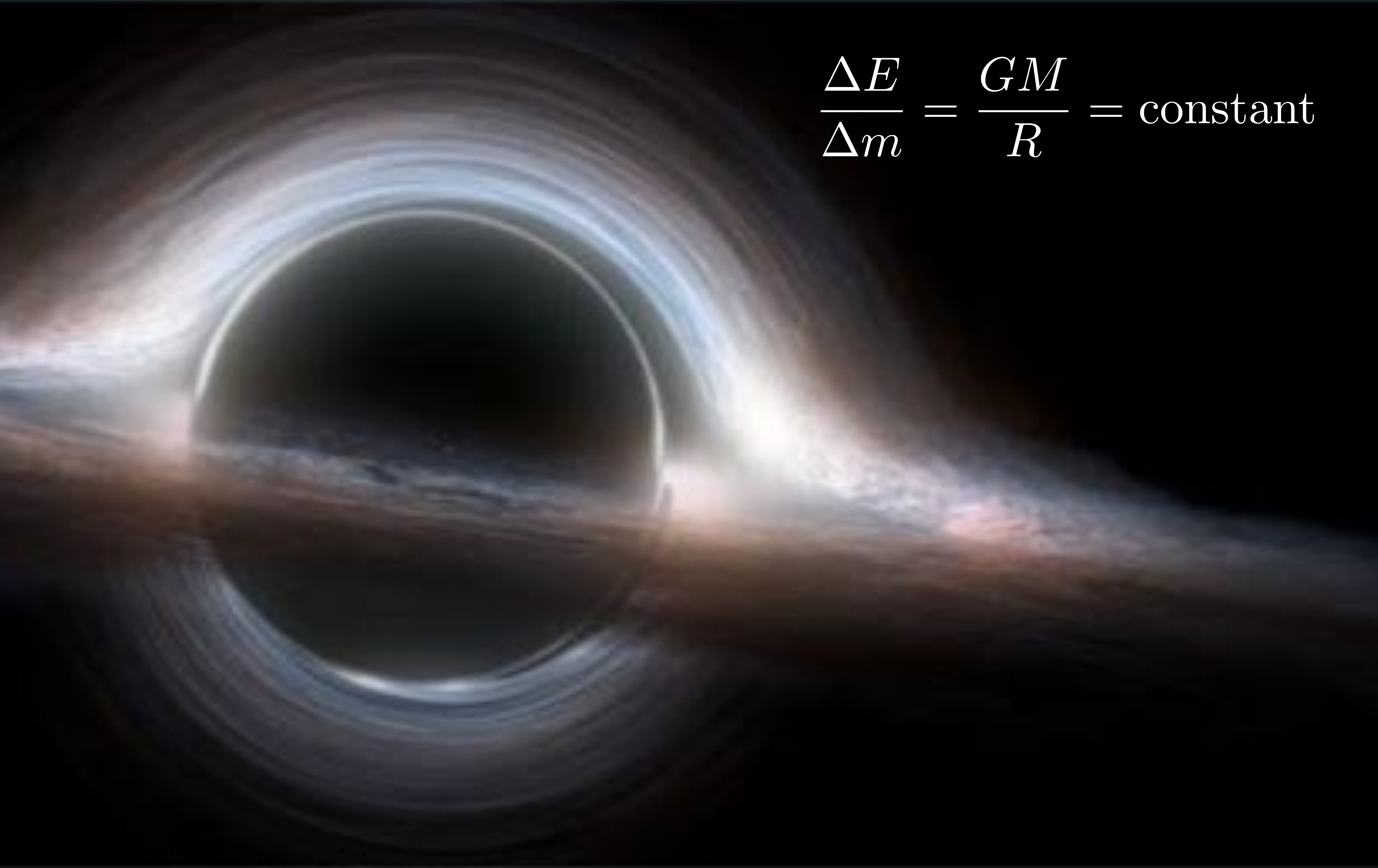
(Grand) Unification (Theory)
CV-BH-NS-ULX-AGN

Guillaume Dubus

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble
CNRS
UNIVERSITÉ GRENOBLE ALPES

Porquerolles Sep. 2017

Why look for unification ?



$$\frac{\Delta E}{\Delta m} = \frac{GM}{R} = \text{constant}$$

Scale-invariant jets

Heinz & Sunyaev 2003

radio emission is synchrotron from a continuous jet scaled to R_g

dimensional analysis yields

$$L_r \propto M^{17/12-\alpha/3}\, \dot{m}^{17/12+2\alpha/3} \propto \dot{M}^{1.4}$$

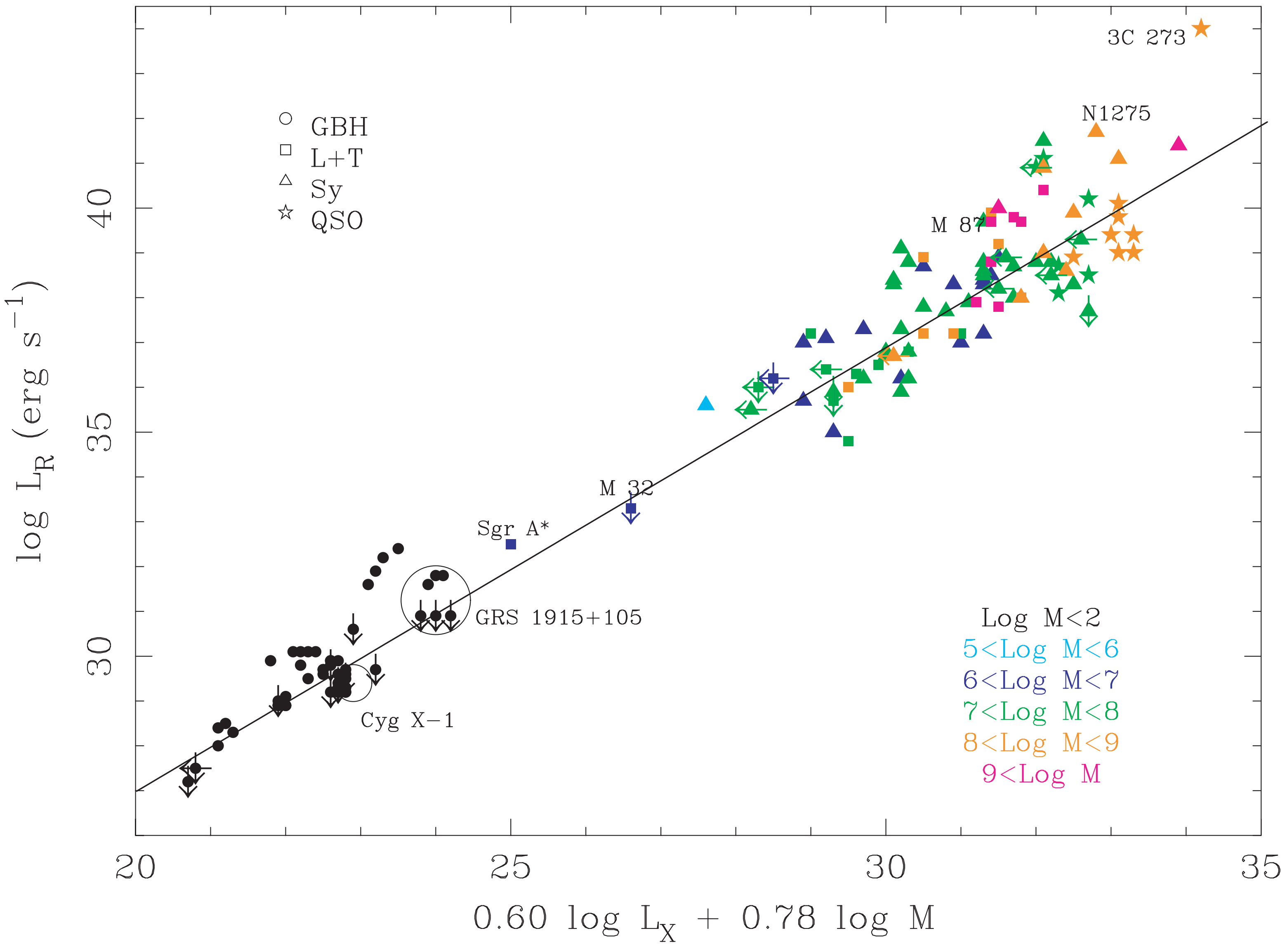
relate $\dot{M}$ to X-ray luminosity

$$l_x \propto \dot{m}^{\xi}$$

then

$$\log L_r = \frac{1.4}{\xi} \log L_X + \frac{1.4(\xi-1)}{\xi} \log M$$

Fundamental plane of BH accretion



Merloni, Heinz, Di Matteo 2003

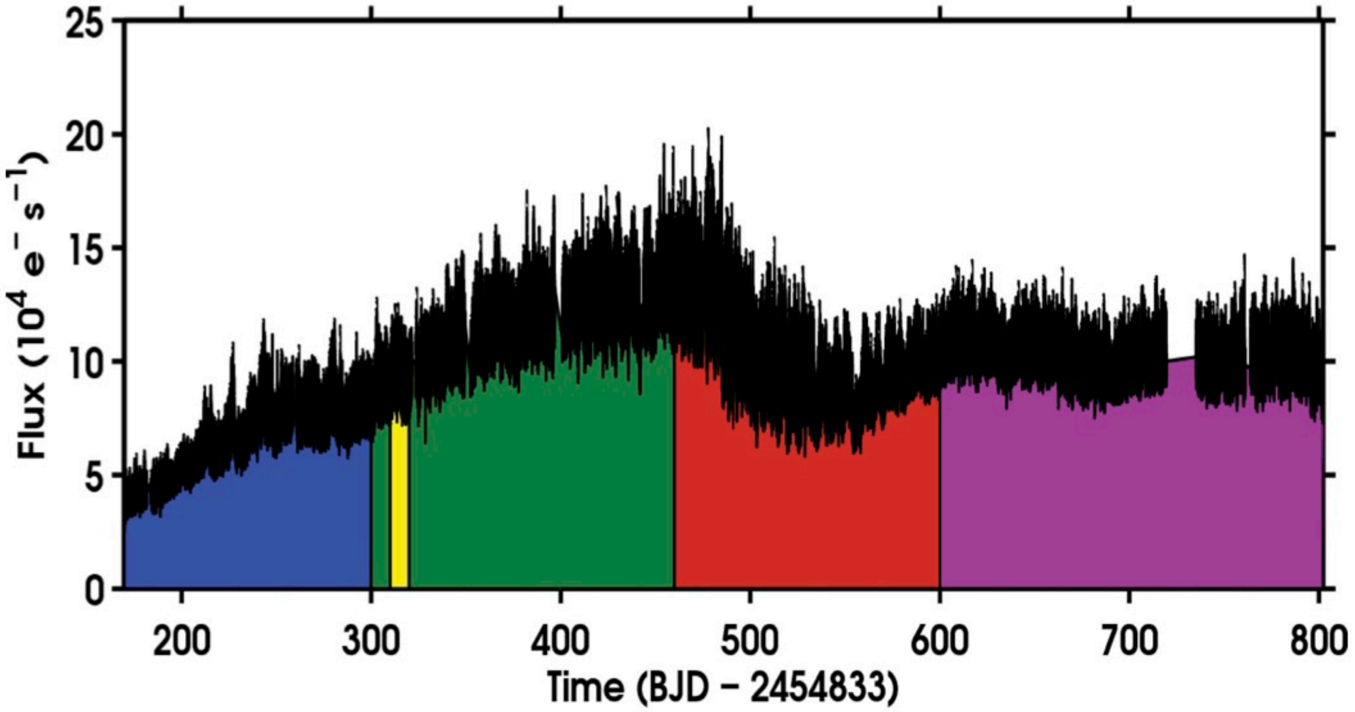
Falcke, Körding, Markoff 2004

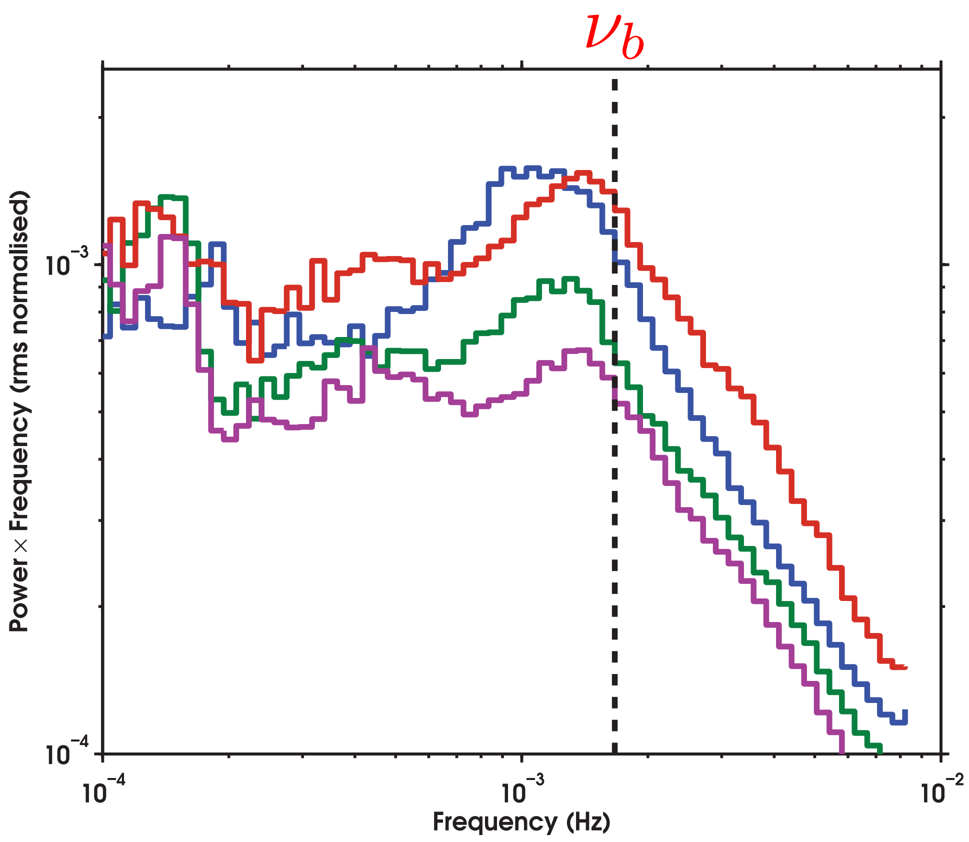
(with $\xi \approx 2$ favouring radiatively-inefficient accretion)

Flickering in accreting objects

CV lightcurve (MV Lyr)

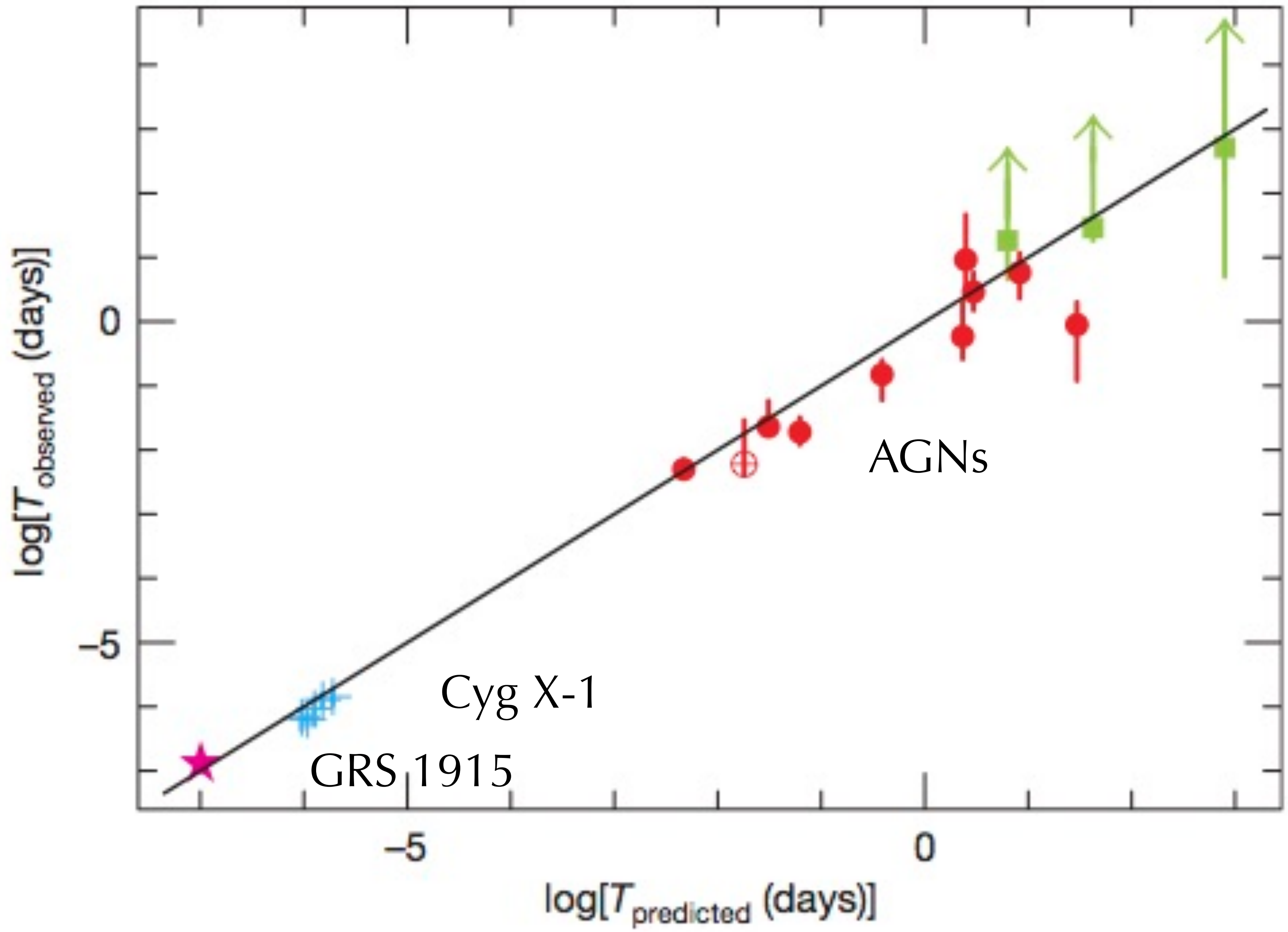
power spectrum





Scaringi 2012

Fundamental plane of black hole variability



McHardy+2006

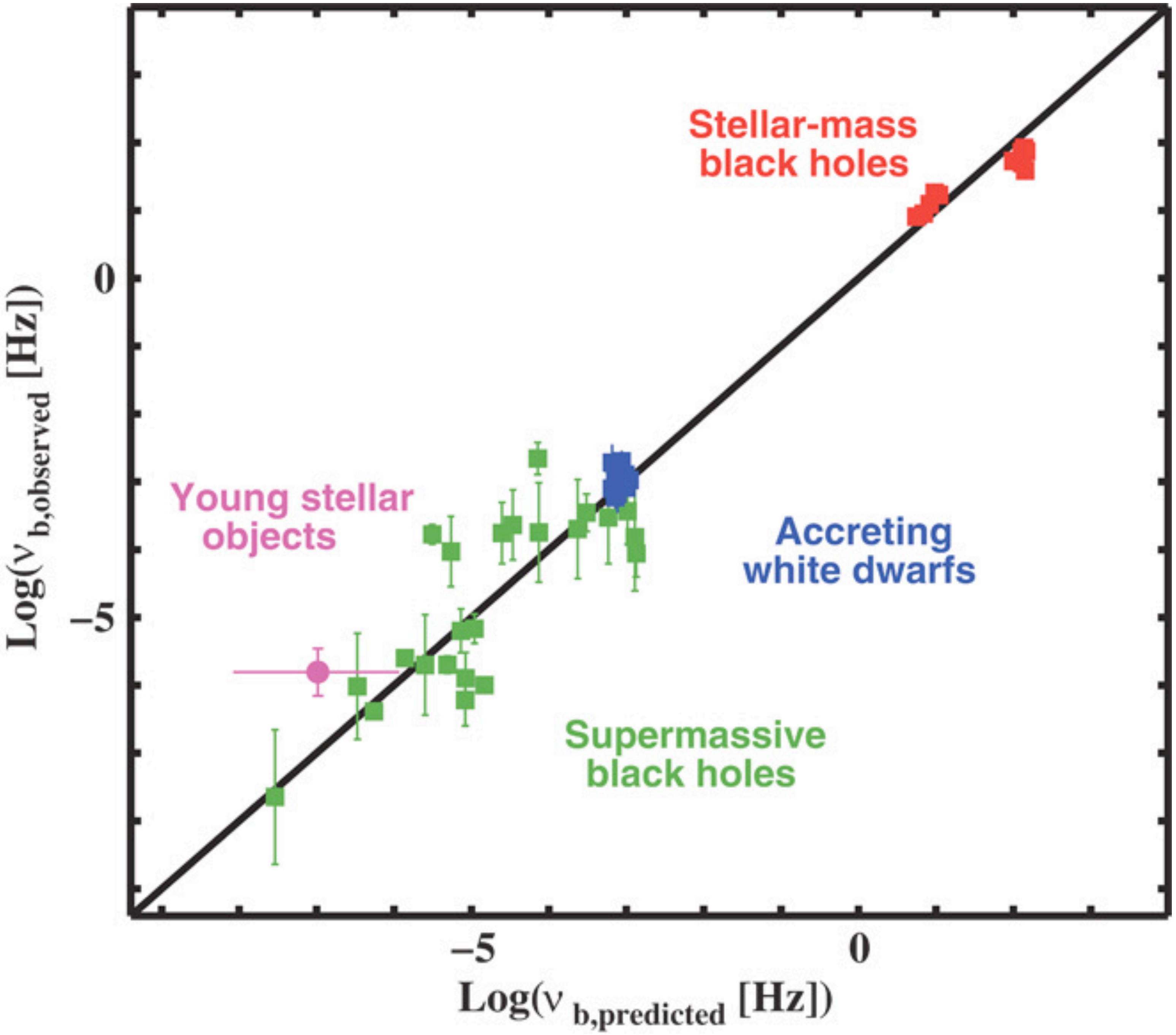
break frequency ν_b scales as

$$\nu_b \sim \frac{\dot{M}}{M^2}$$

i.e. scale-free

$$\frac{\nu_b}{\nu_K} \sim \dot{m}$$

Fundamental plane of accretion variability



Scaringi+ 2015

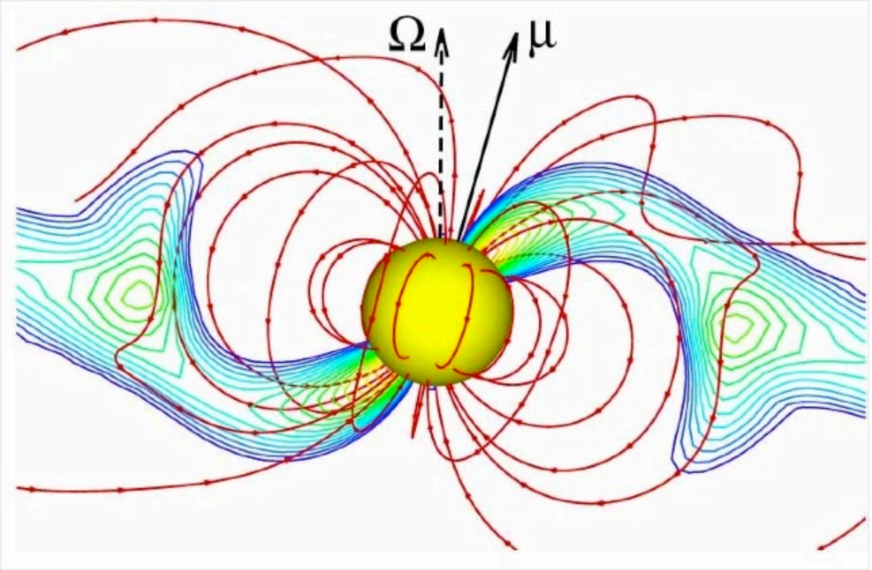
break frequency actually scales as

$$\nu_b \sim \frac{\dot{M}}{R_\star^2}$$

what sets the scaling ?!

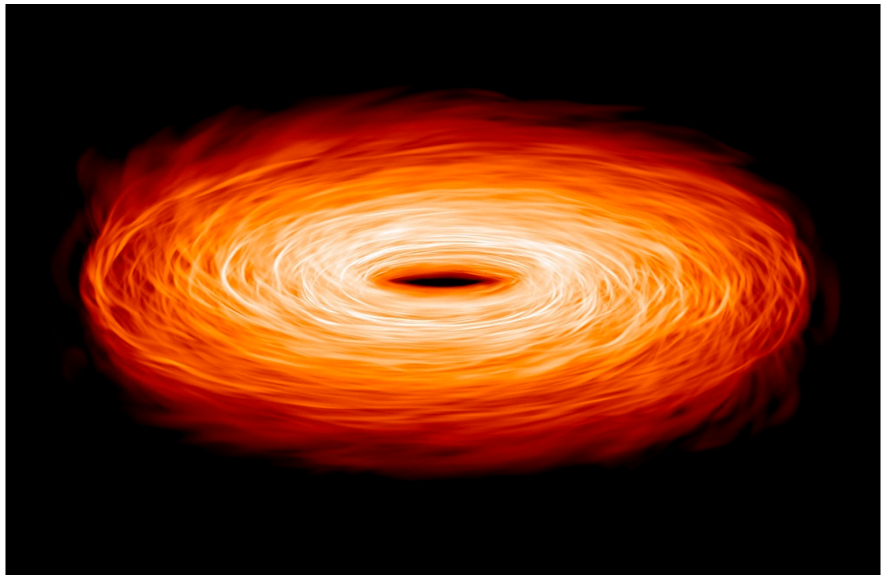
Physics common to accreting objects

disk magnetosphere interaction



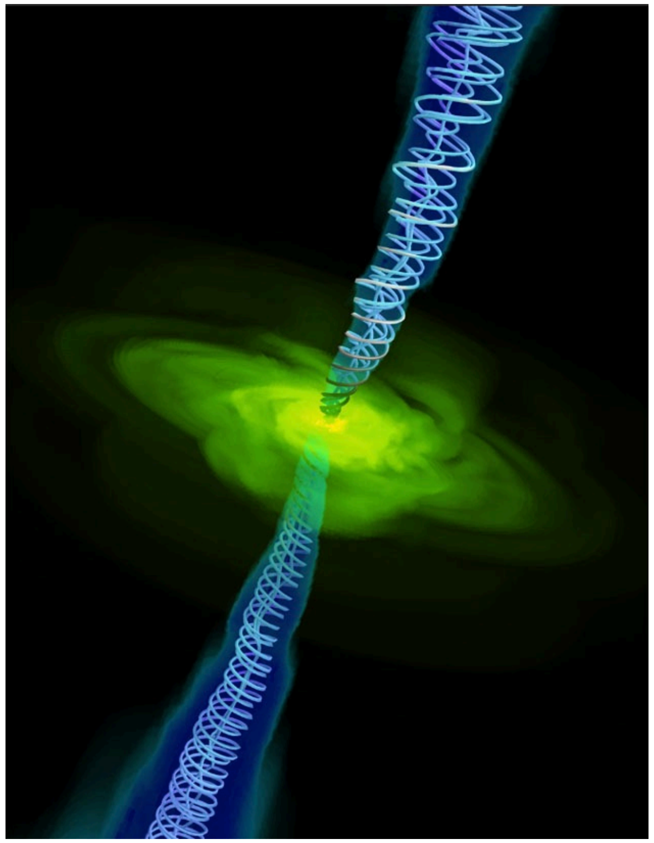
Romanova+ 2004

accretion flows



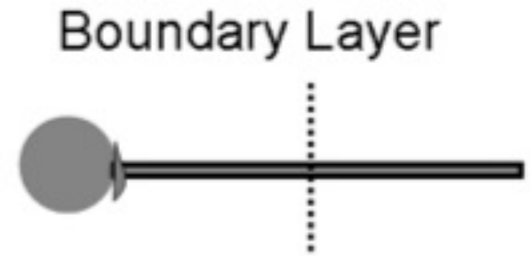
Flock+ 2011

outflows: winds & jets

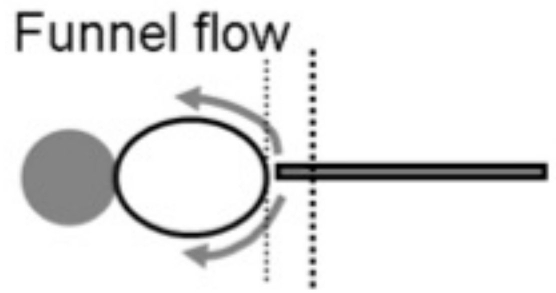


Tchekhovskoy 2016

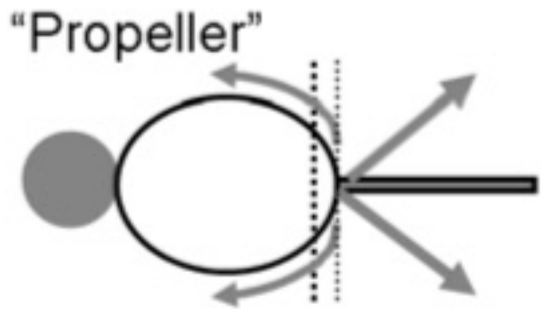
Disk-magnetosphere interaction



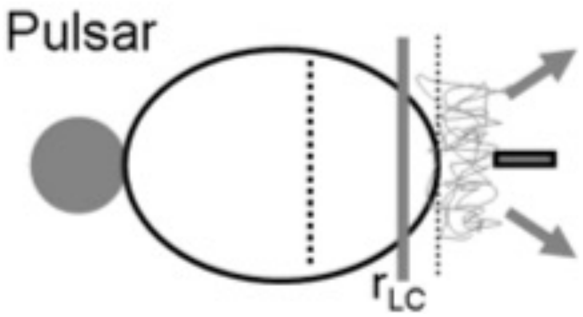
$R_m < R_\star$



$R_\star < R_m < R_{co}$



$R_{co} < R_m < R_{lc}$



$R_m > R_{lc}$

Romanova+2008

physics set by 4 characteristic radii

1. **magnetospheric radius**

$$\beta(R_m) = \frac{P}{P_{B\star}} \approx 1$$

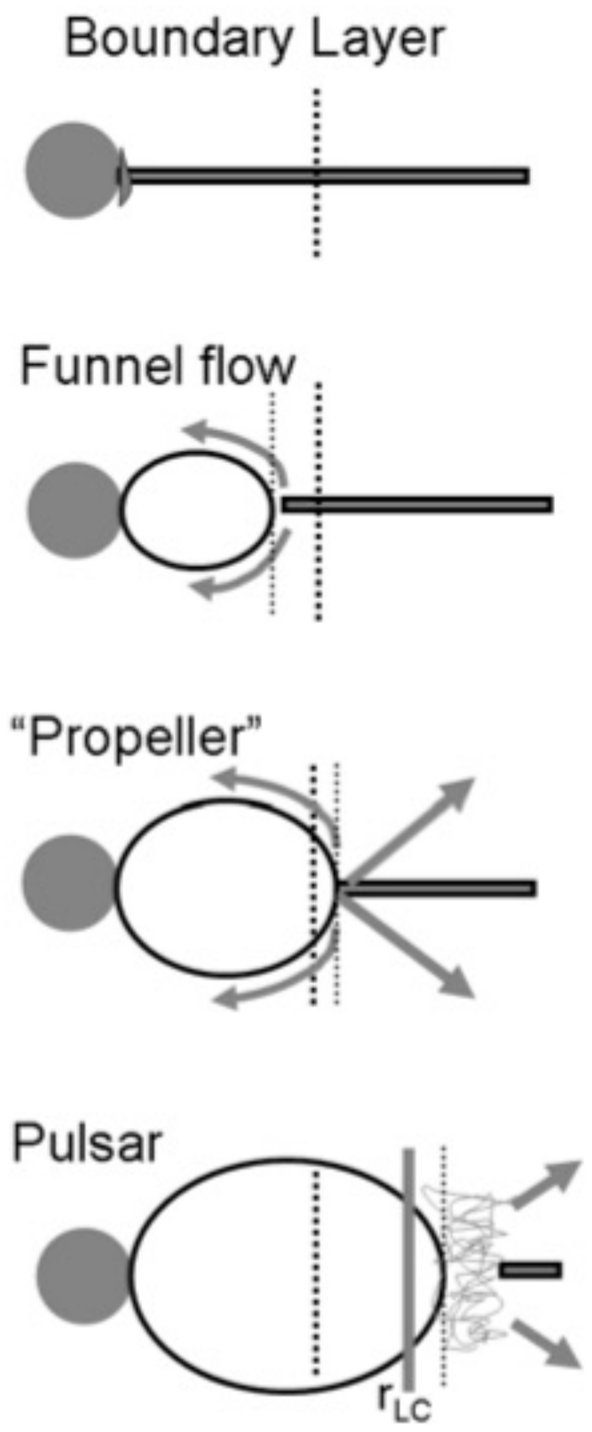
2. stellar radius $R_\star$
3. corotation radius

$$\Omega_k(R_{co}) = \Omega_\star$$

4. light cylinder radius

$$R_{lc} = c/\Omega_\star$$

Disk-magnetosphere interaction



Romanova+2008

dwarf novae & neutron star XRBs in outburst, novae-like

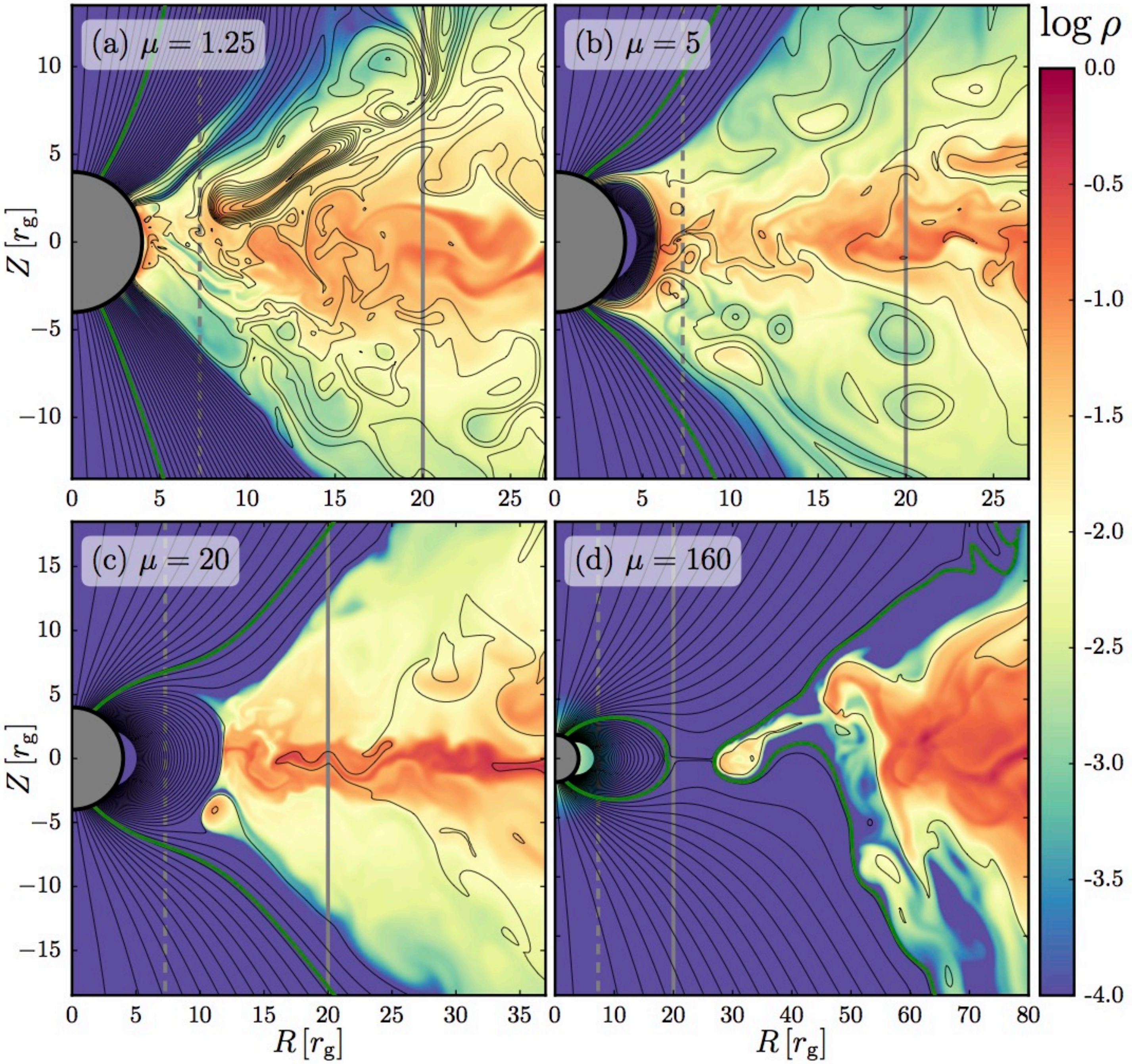
intermediate polars, accreting X-ray pulsars, T Tauri, **ULXs**

AE Aqr, **transitional ms pulsars?**

black widows, γ-ray binaries, **transitional ms pulsars**

Simulations interface well with observations

boundary layer funnel flow



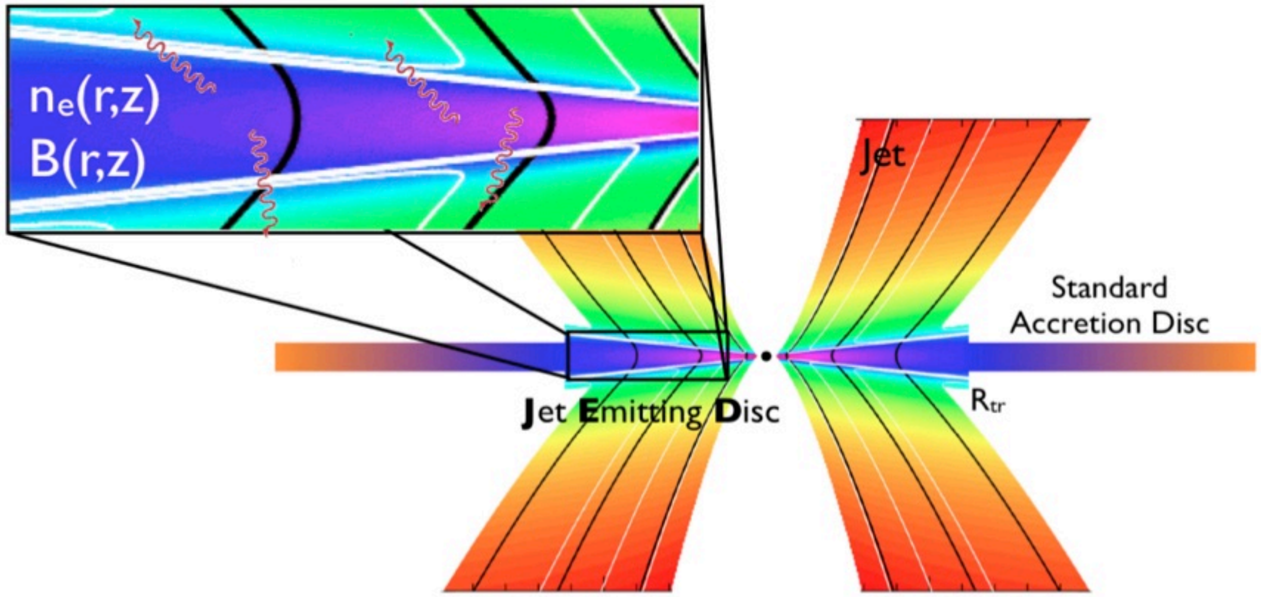
propeller pulsar

Parfrey Tchekhovskoy 2017

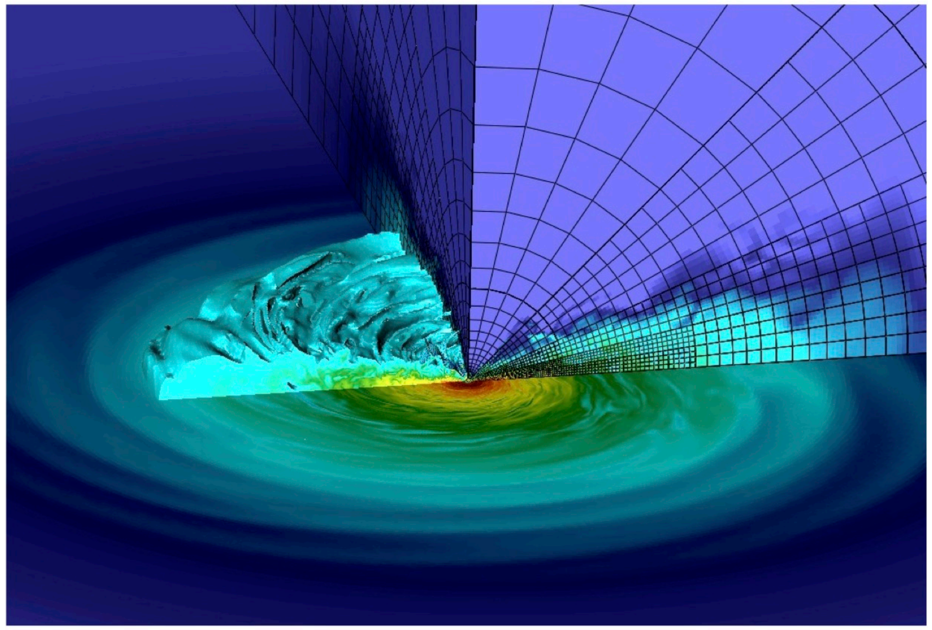
- magnetospheric radius ?
- column accretion ?
- variability ?
- outflows ?
- torques ?

Understanding accretion flows

semi-analytical ⟷ **numerical**



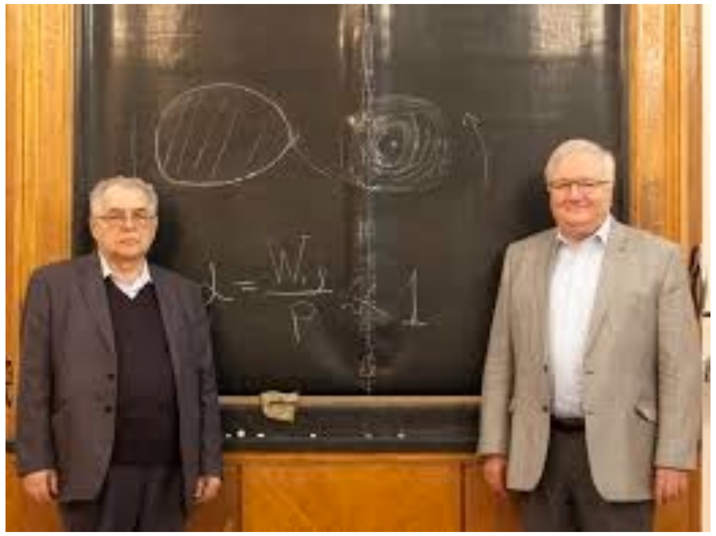
Petrucci, Ferreira



Zhu & Stone 2017

The basic unifying theory of accretion flows

Shakura Sunyaev 1973



radiatively-efficient thin disks

angular momentum transport

$$\frac{\partial R^2\Omega\Sigma}{\partial t} = \frac{1}{2\pi R}\frac{\partial}{\partial R}\left[R^2\Omega\left(\dot{M} - 3\pi\nu\Sigma\right)\right]$$

turbulent viscosity parametrised as

$\nu \sim \alpha c_s H$ i.e. stress is $W_{r\phi} = \alpha P$

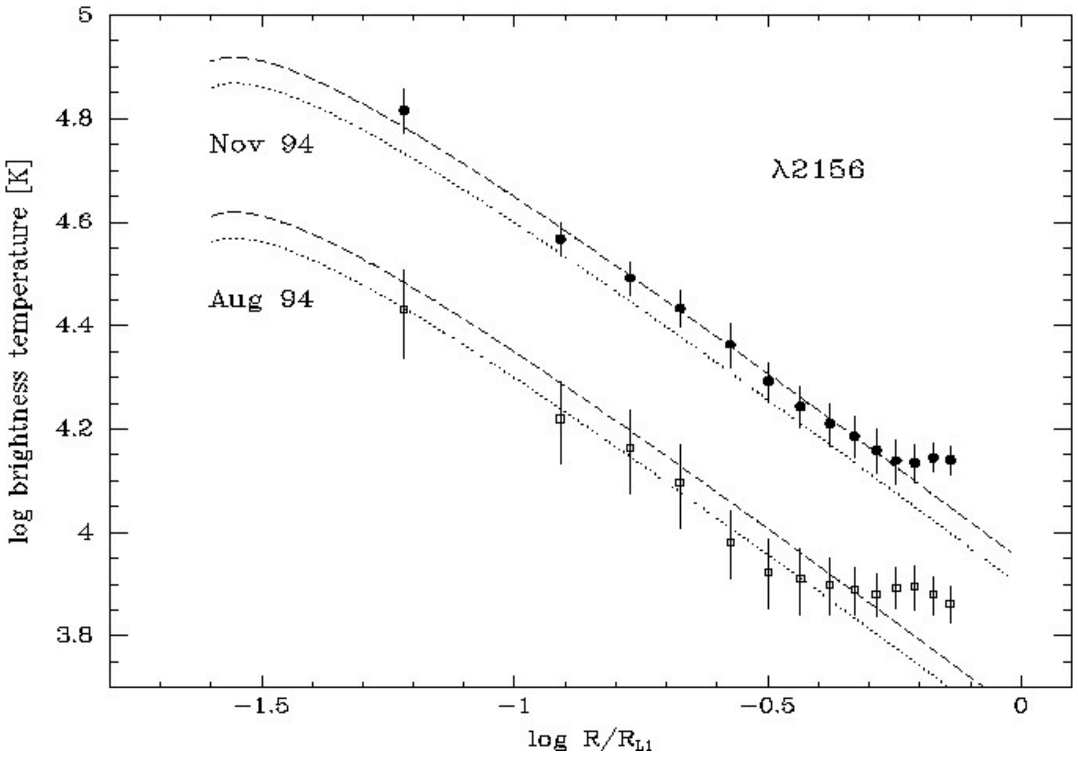
cooling balances heating

$$\sigma T_{\rm eff}^4 = \frac{9}{8}\nu\Sigma\Omega^2$$

Evidence for thin disks in binaries

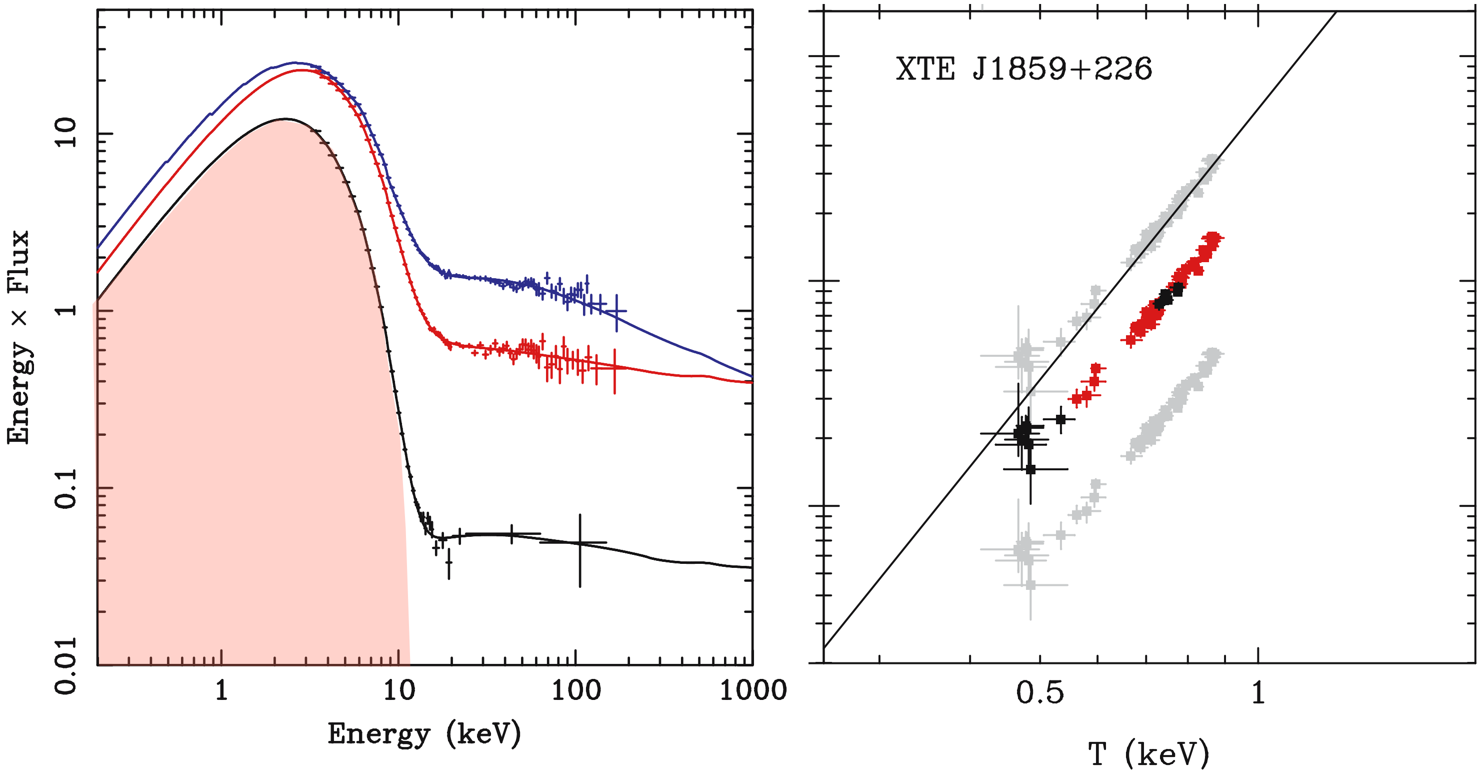
In steady state $T_{\rm eff} \propto (\dot m/m)^{1/4} r^{-3/4}$

Eclipse mapping in CVs



Baptista & Horne 1994

Disk blackbody in XRBs with $L \propto T^4$



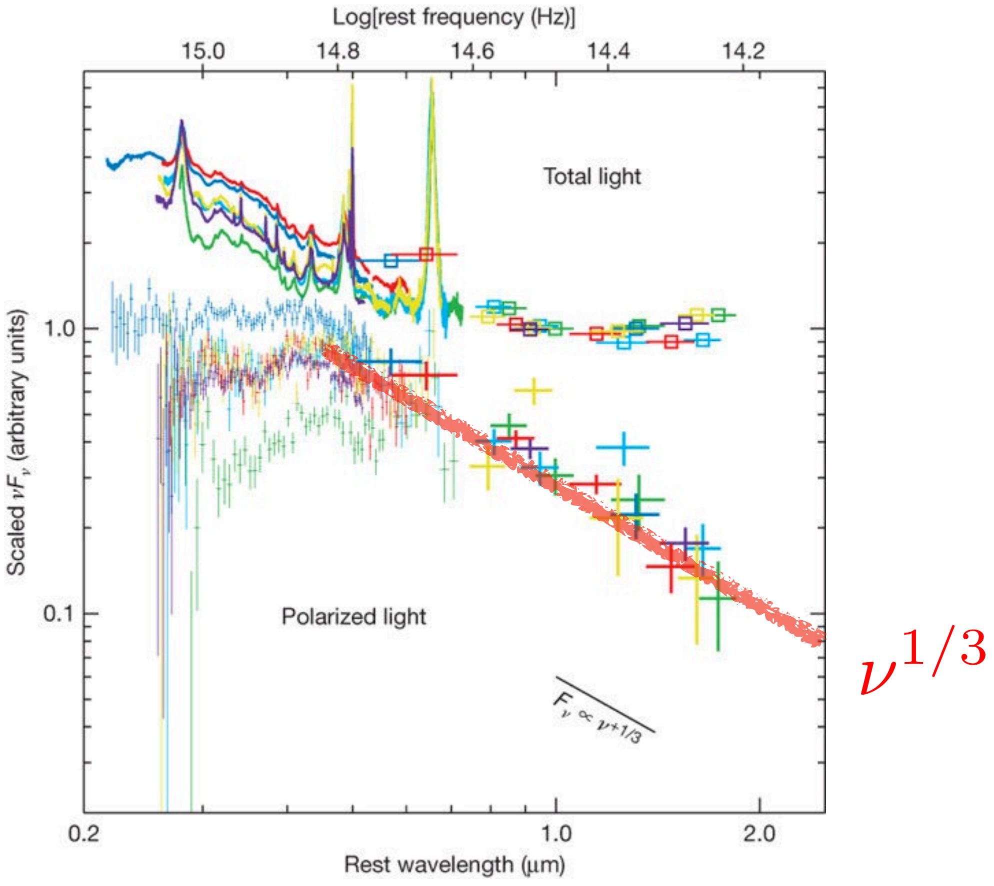
Done+ 2007

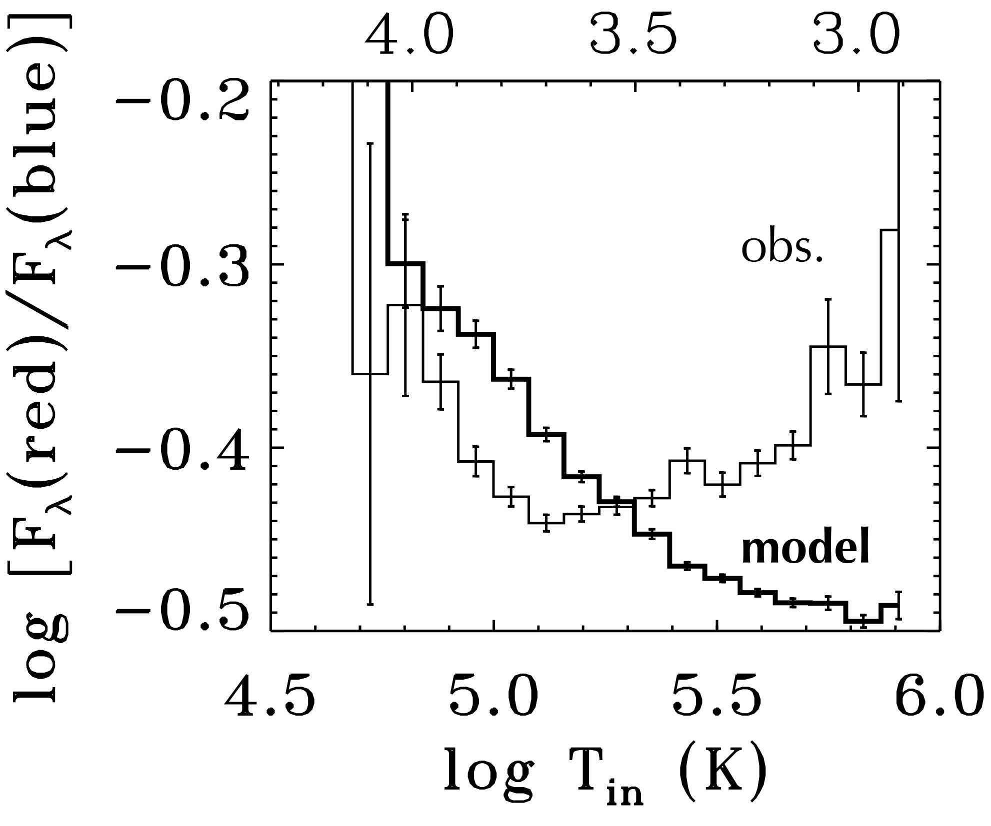
Evidence for thin disks in AGNs ?

thin disk signature harder to find, if present at all

disk bb in quasar polarised light

UV continuum does not follow expectations





Kishimoto+ 2008

Davis+ 2007

Conditions in disks are NOT scale free

physical conditions in the disk depend on thermodynamics, opacities, etc.

radiation pressure very strong in AGNs

$$r_{\rm rad}/r_S \approx 1400\, \alpha_{0.1}^{2/21} m_8^{2/21} \dot{m}^{16/21}$$

(Shakura Sunyaev 1973)

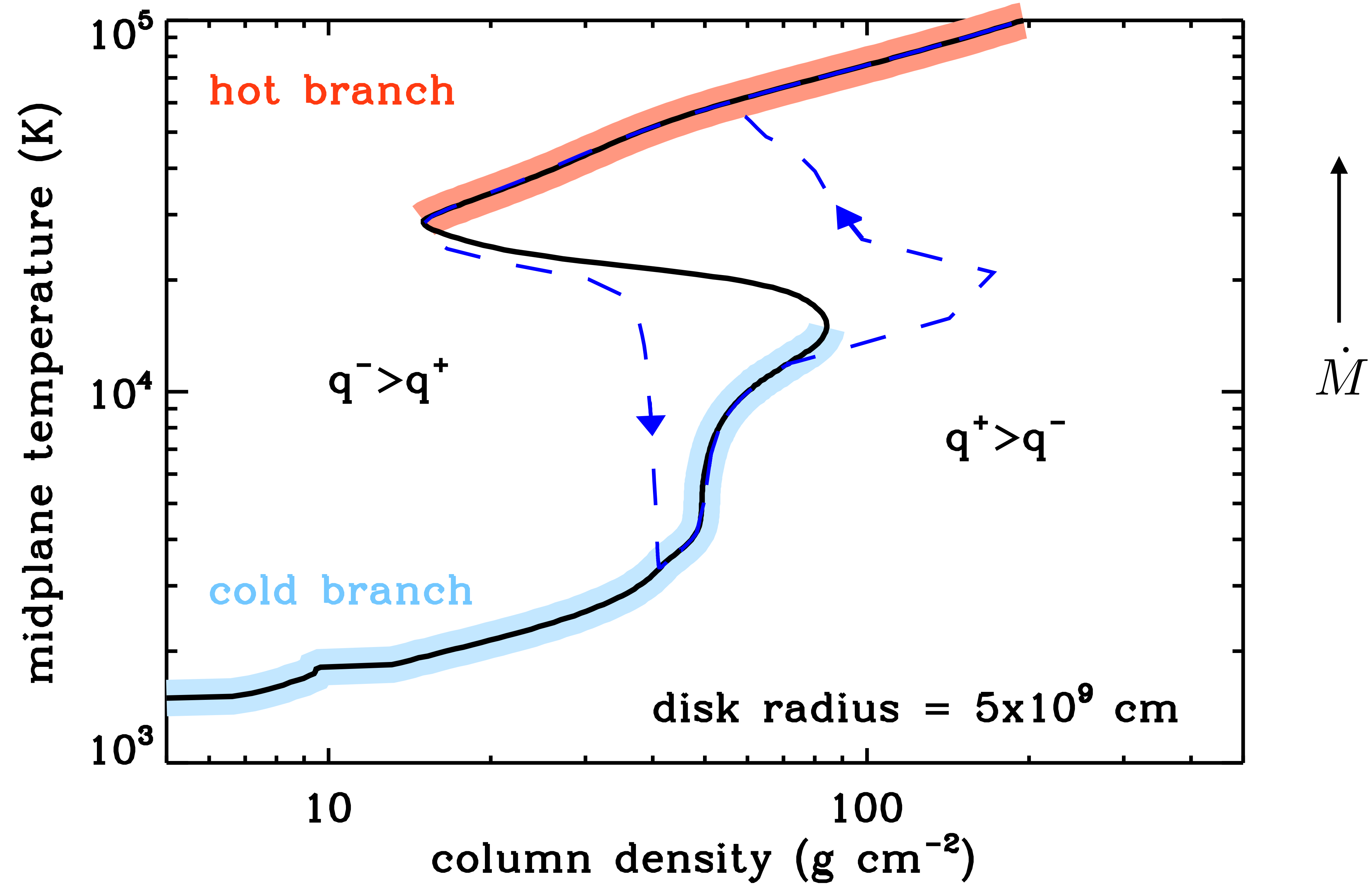
self-gravity limits the disk size

$$r_{\rm sg}/r_S \approx 620\, \alpha_{0.1}^{14/27} m_8^{-26/27} \dot{m}^{-8/27}$$

(Kawaguchi+ 2014)

Disk Instability Model (DIM)

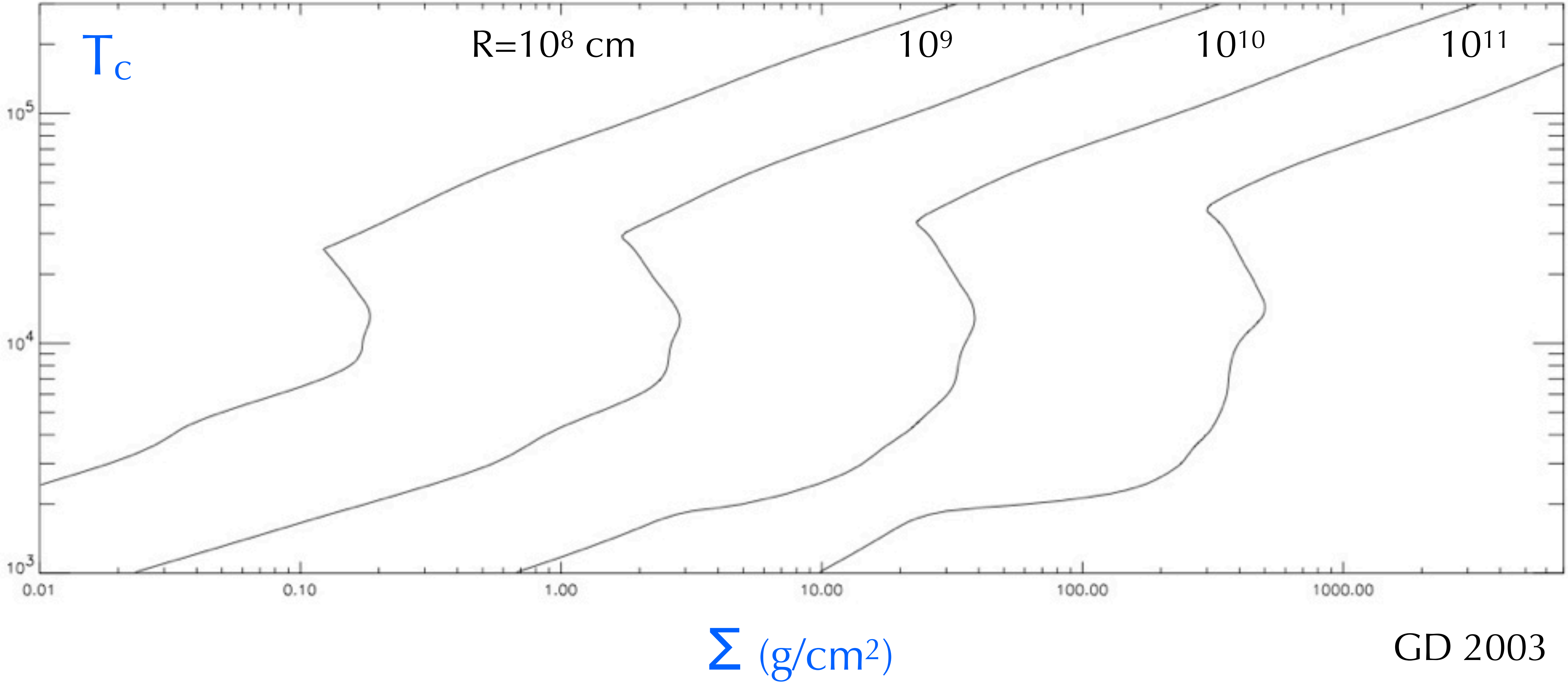
Thermal equilibrium of a thin ring shows hysteresis



Dubus, Porquerolles 9/2017

Stability of a thin accretion disk to the DIM

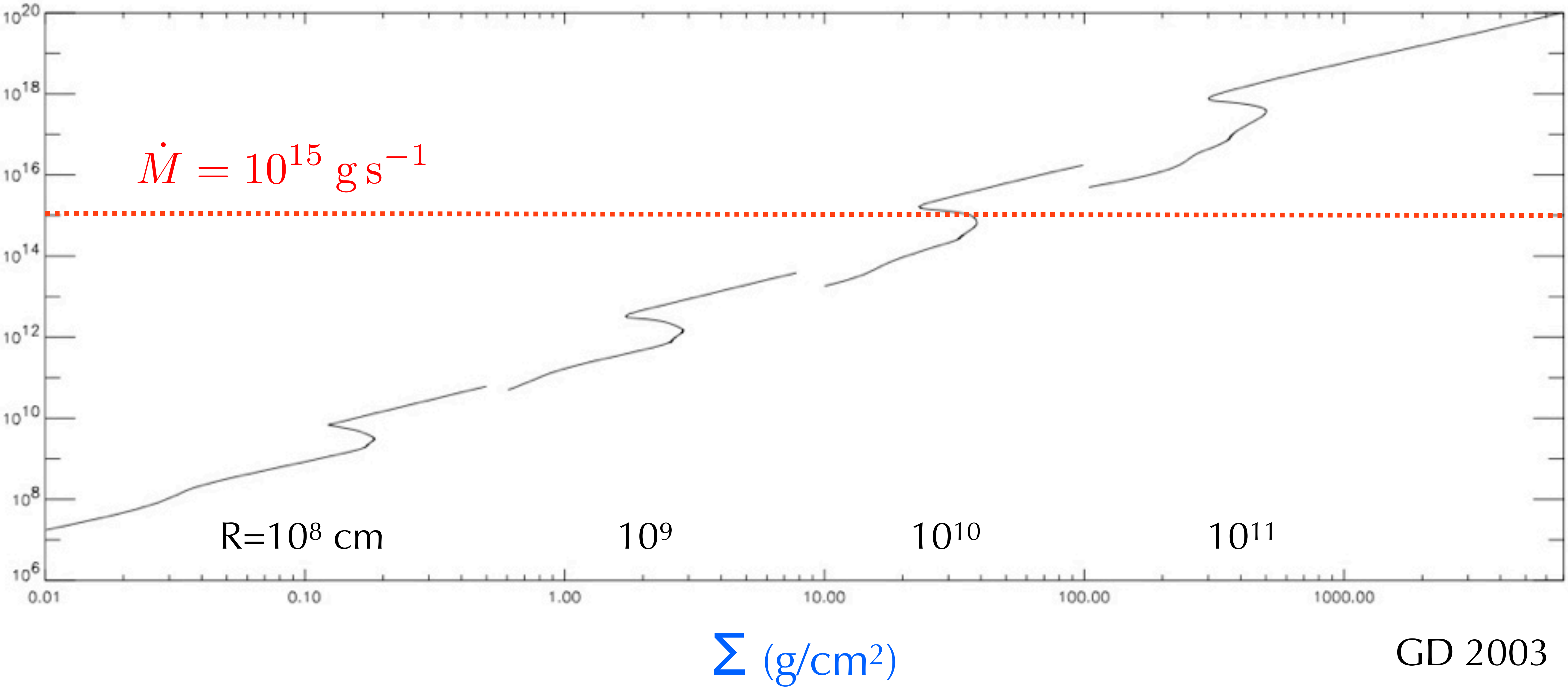
There is an S-curve for each radius and choice of α



GD 2003

Critical mass accretion rate for stability

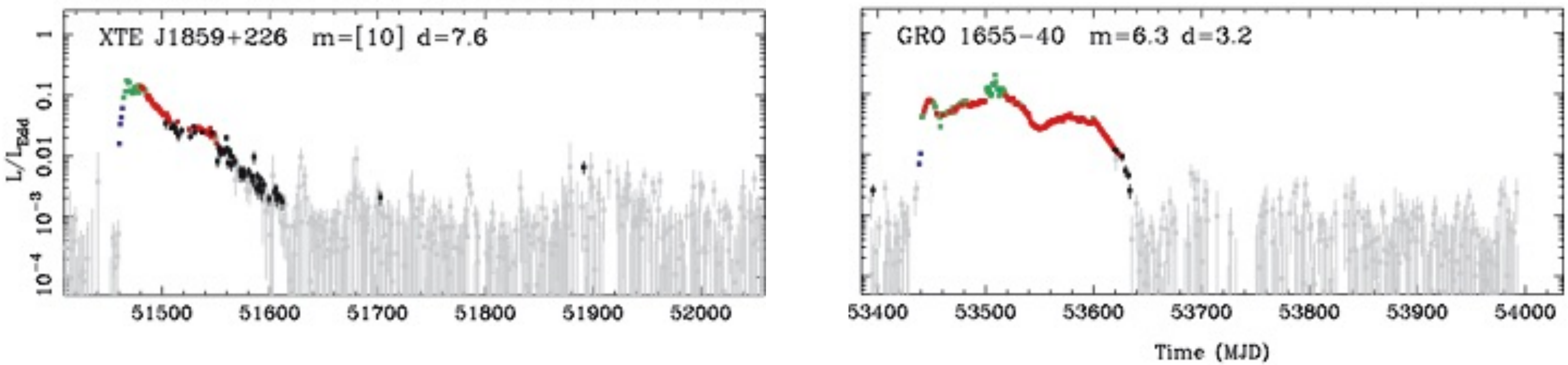
e.g. disc with a size > 10^{10} cm is unstable if mass transfer rate <10^{15} g s^{-1}



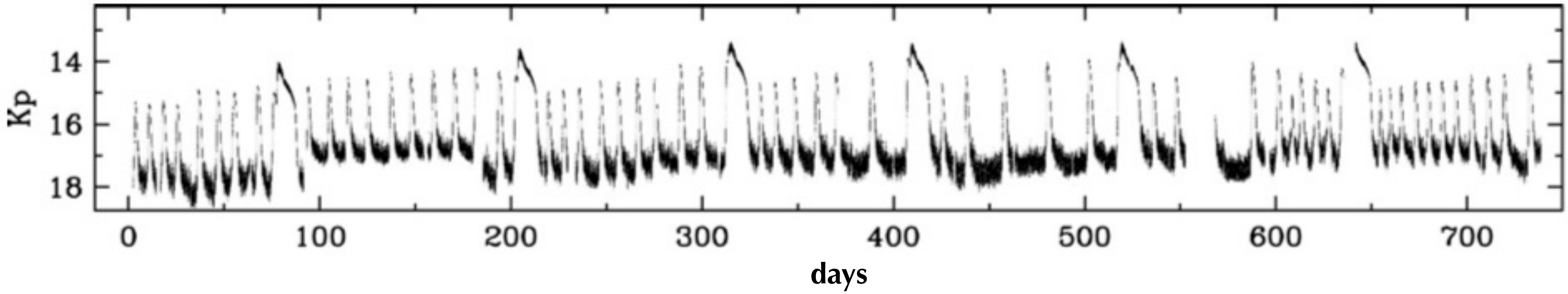
GD 2003

DIM drives changes in mass accretion rate

X-ray binaries (Done+ 2007)



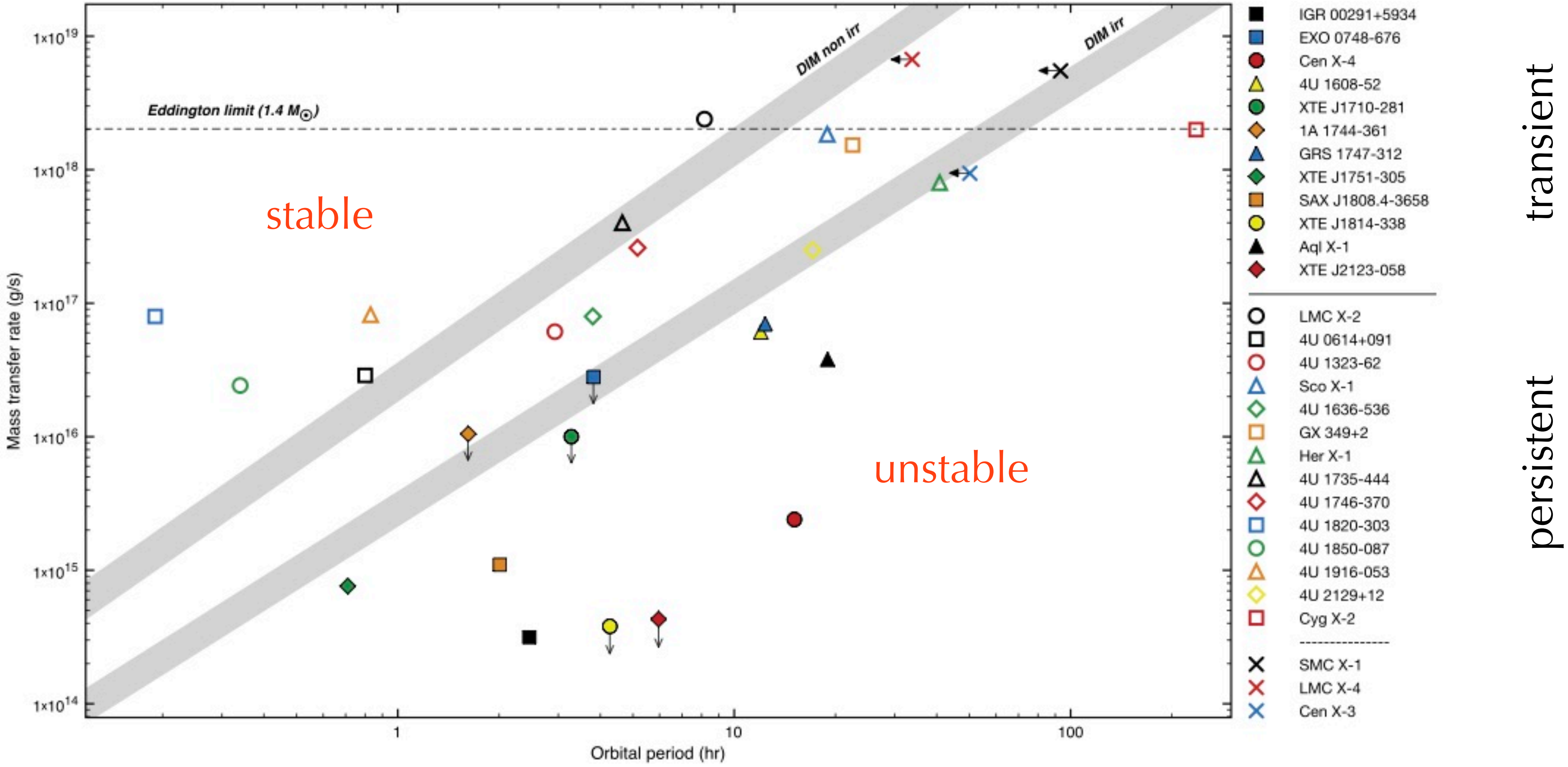
dwarf novae (Cannizzo+ 2012)



[DIM likely irrelevant in AGNs: Hameury+ 2009]

DIM explains (in)stability of XRBs

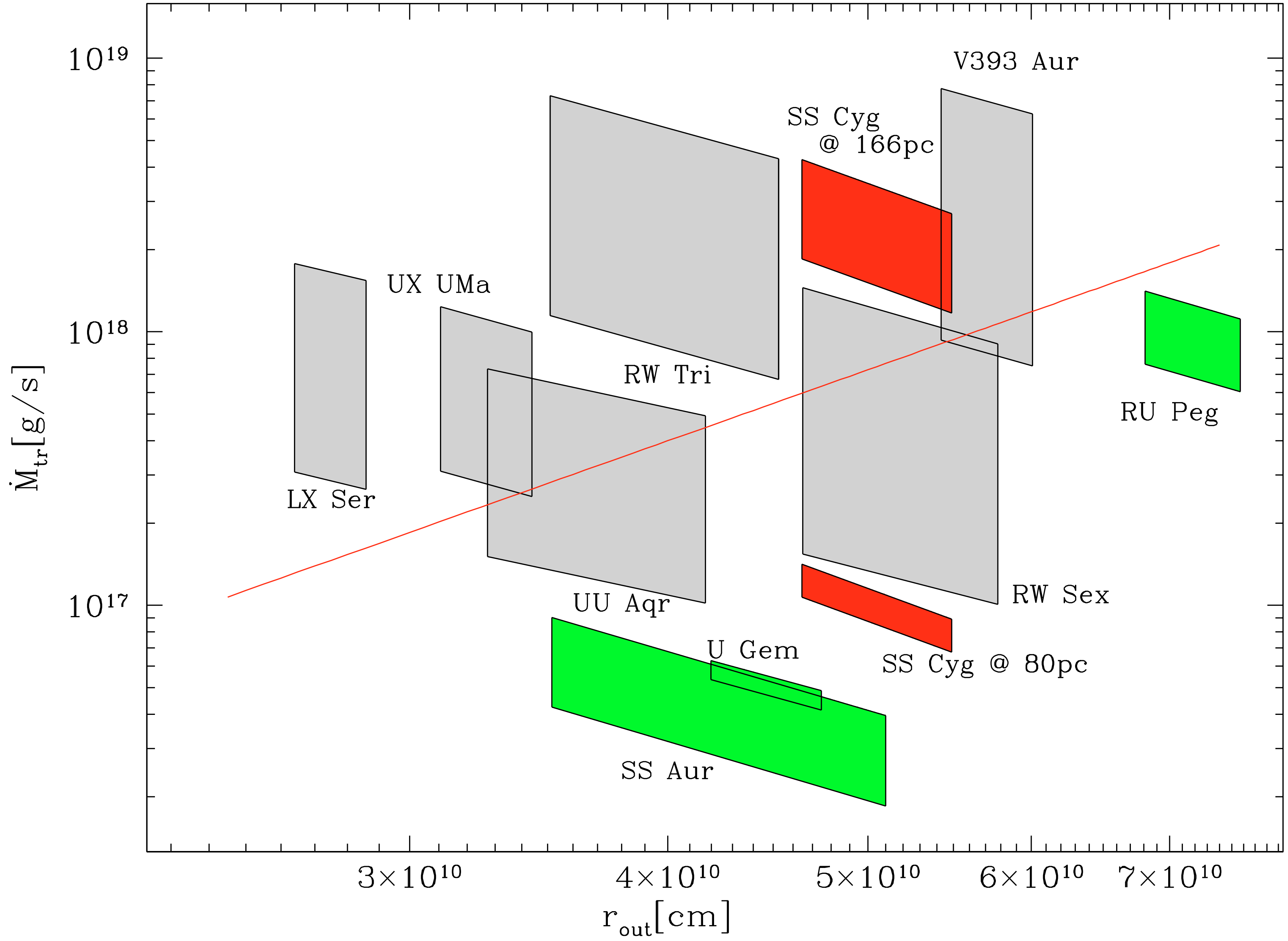
stability depends on mass transfer rate & disk size (& irradiation), not α



Coriat+ 2012

Is the dwarf nova SS Cyg stable? YES

Schreiber & Lasota 2007 (Smak 1982)



SS Cyg @ 117 pc
(Miller-Jones+ 2013)

big step forward from GAIA distances + Kepler/LSST lightcurves

Getting the right lightcurve

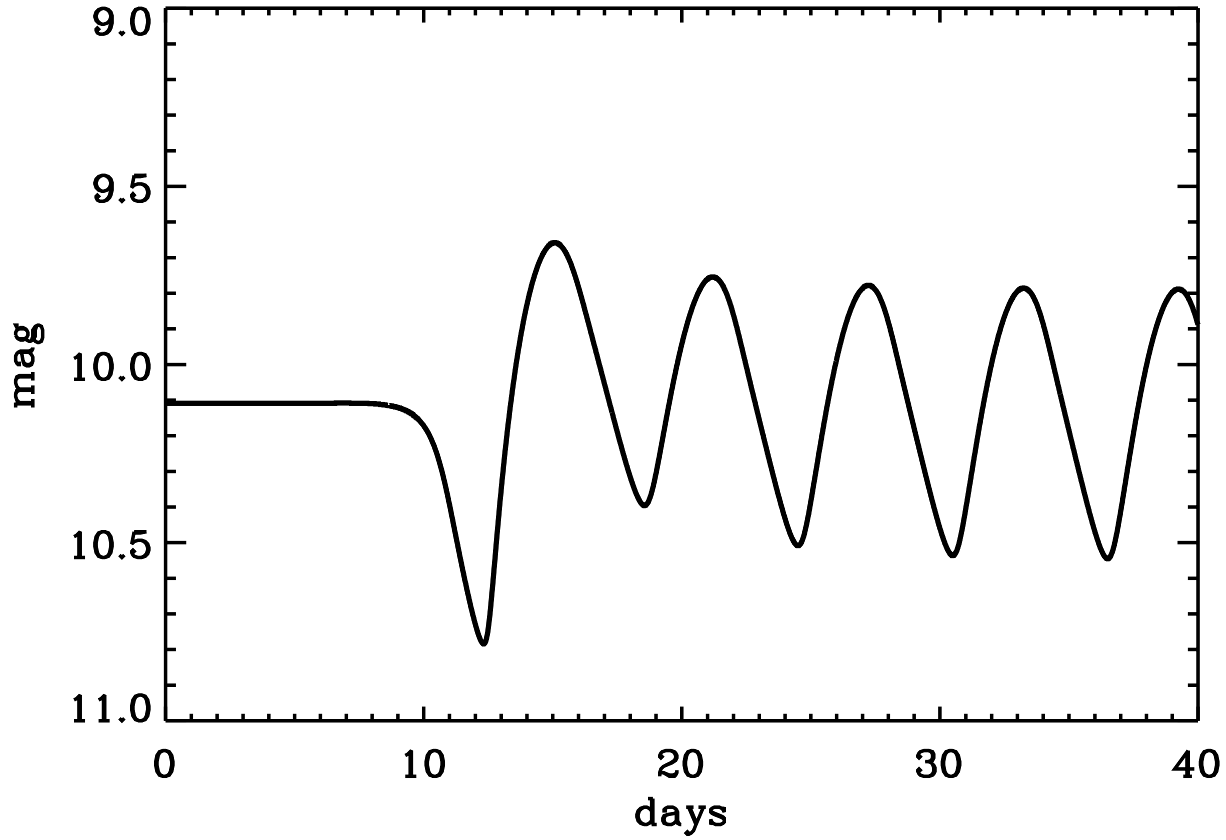
requires additional ingredients:

- change in α with temperature
- truncation due to magnetosphere
- switch from thin disk to hot accretion flow
- irradiation by central object or inner disk
- variable mass transfer from companion
- tidal torques
- stream impact heating
- outflows
- …

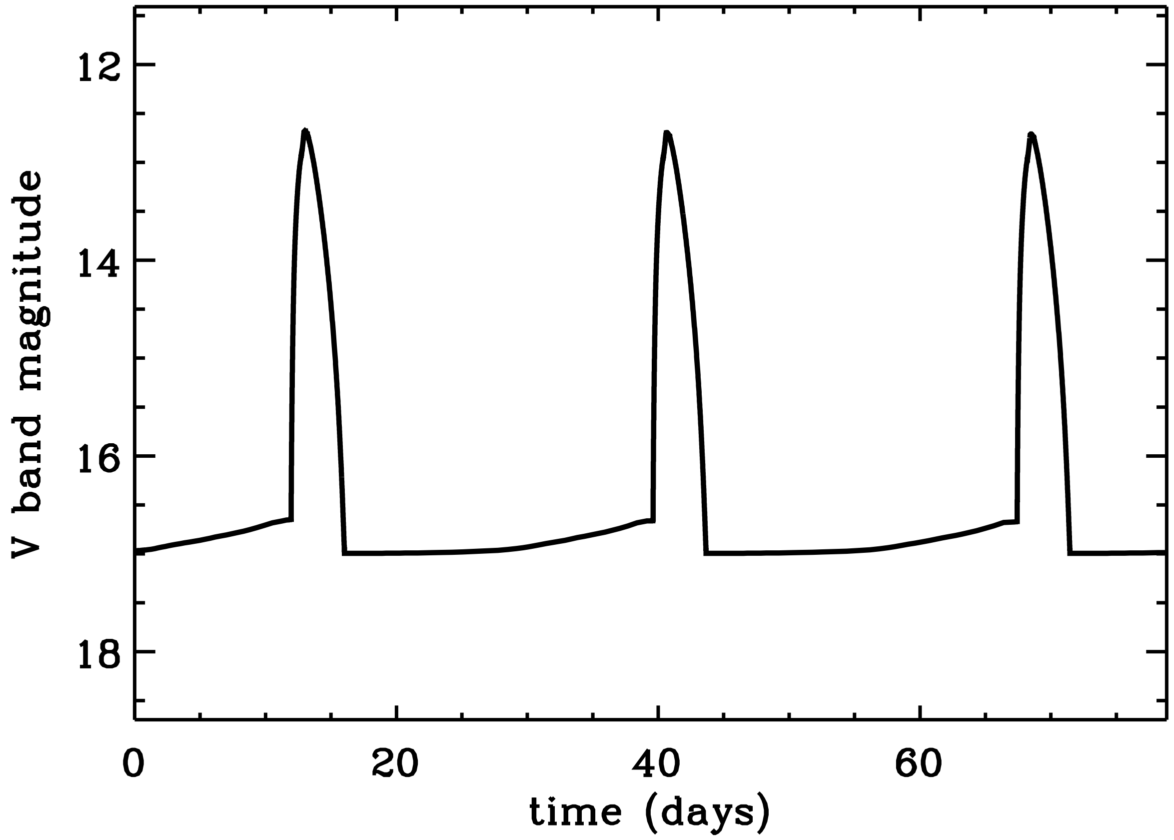
Model outburst lightcurves

higher α with T required in dwarf novae and transient LMXBs

$\alpha=0.04$

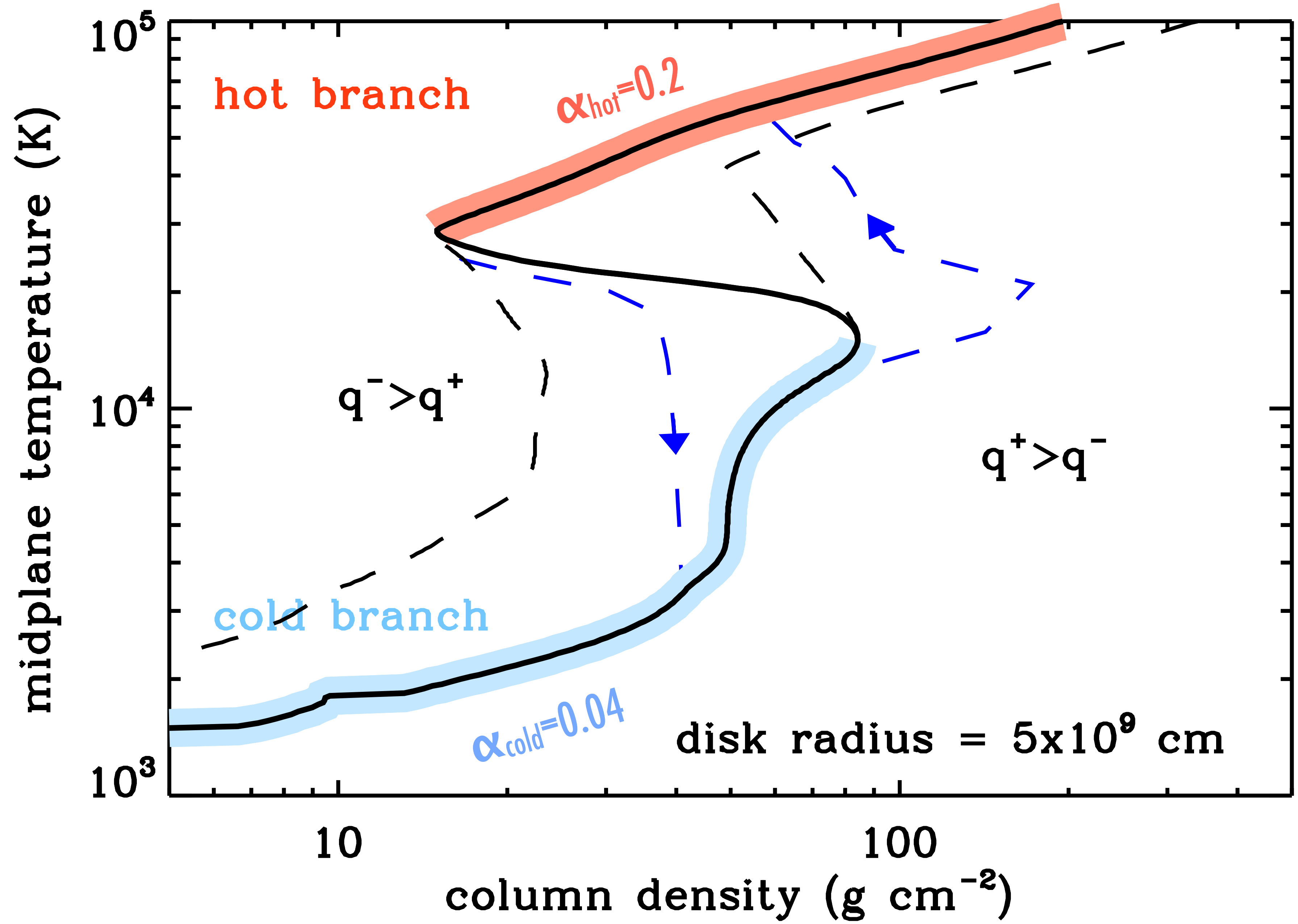


$\alpha_{hot}=0.2$, $\alpha_{cold}=0.04$



Enhanced transport on hot branch

Thermal equilibrium of a thin ring shows hysteresis



Dubus, Porquerolles 9/2017

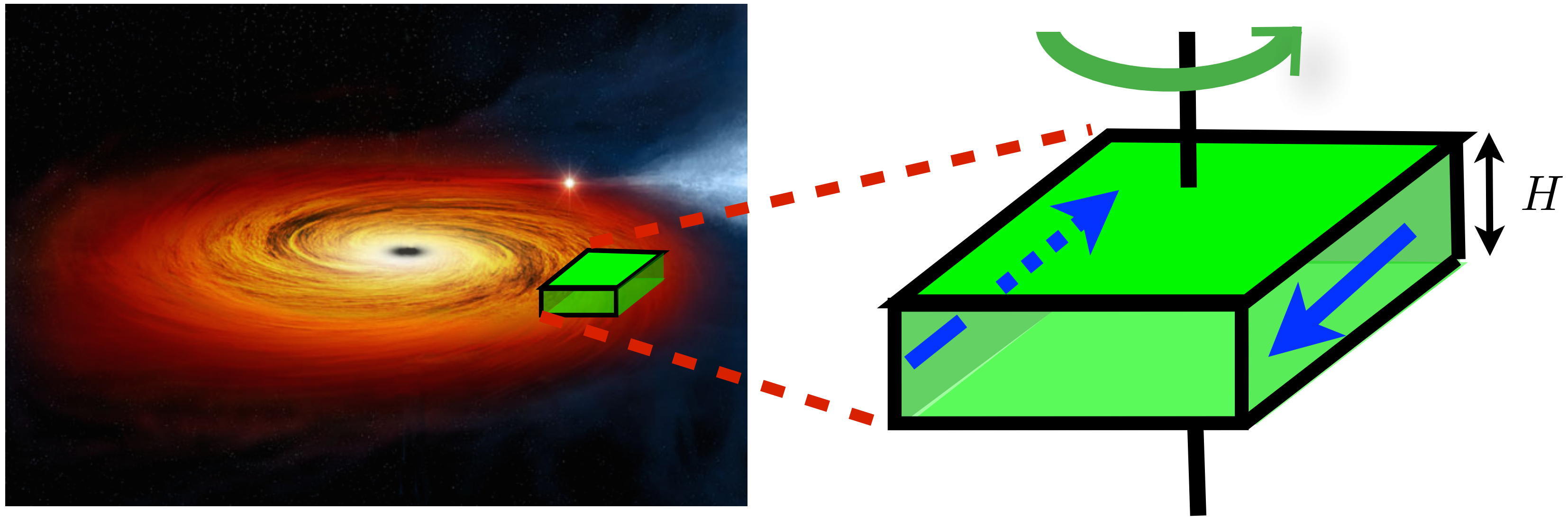
Basic unifying process: MRI-driven transport

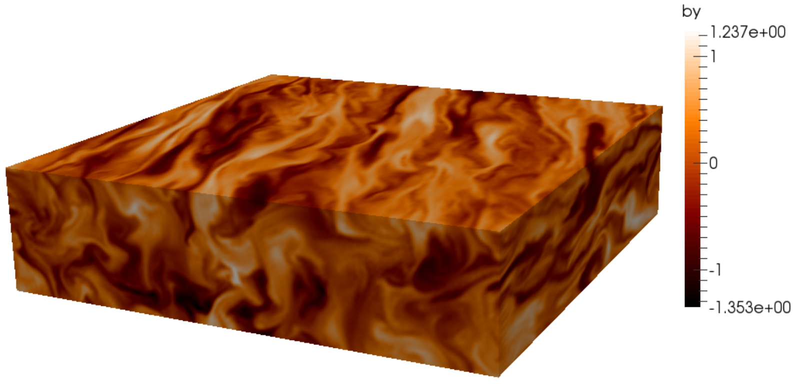
Turbulence generated by **M**agneto-**R**otational **I**nstability in weakly magnetised sheared flows

$$W_{r\phi} = \langle \rho (v_r v_\phi - v_{Ar} v_{A\phi}) \rangle \equiv \alpha \langle P \rangle$$

Balbus Hawley 1991

Measure **α** from local (shearing box) simulations [unification!]

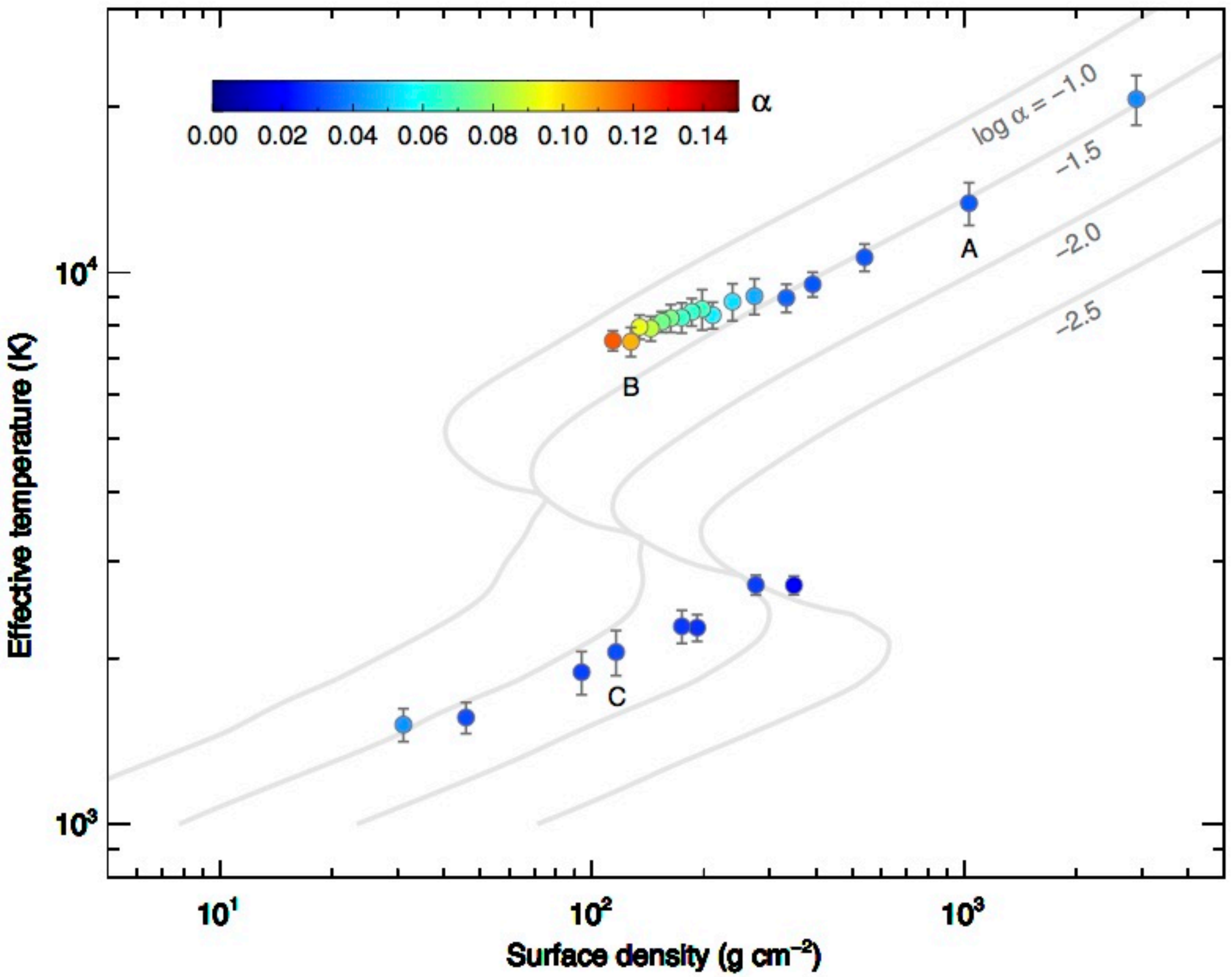




courtesy G. Lesur

caveat emptor: numerical and physical convergence (e.g. Ryan+ 2017)

Evidence for α(T) in MRI simulations



Hirose+ 2014

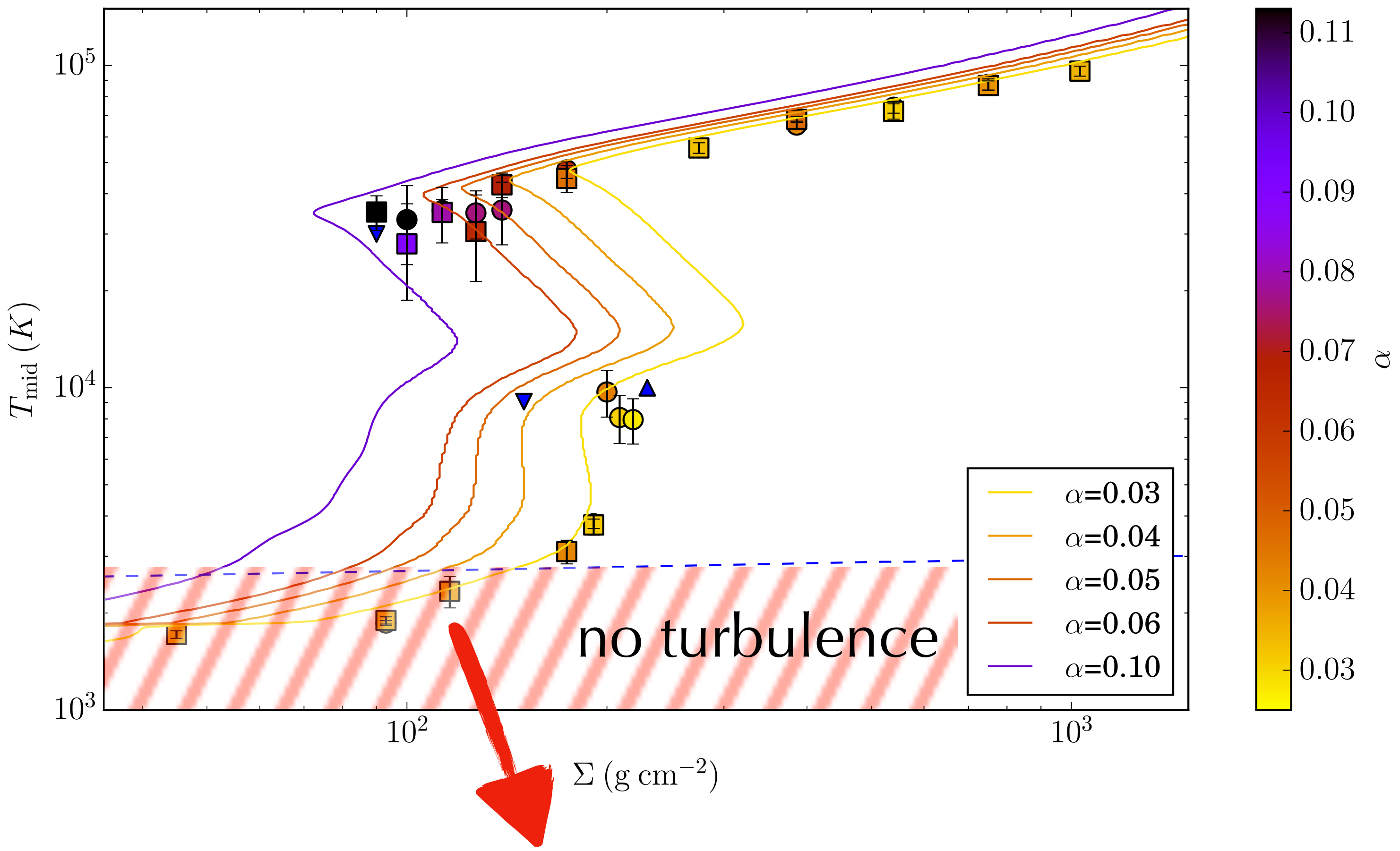
- stratified shearing box
- no net magnetic flux
- radiative transfer
- ideal MHD
- opacities & thermodynamics appropriate to DN (& XRBs)

S-curve still present (Latter+ 2012)

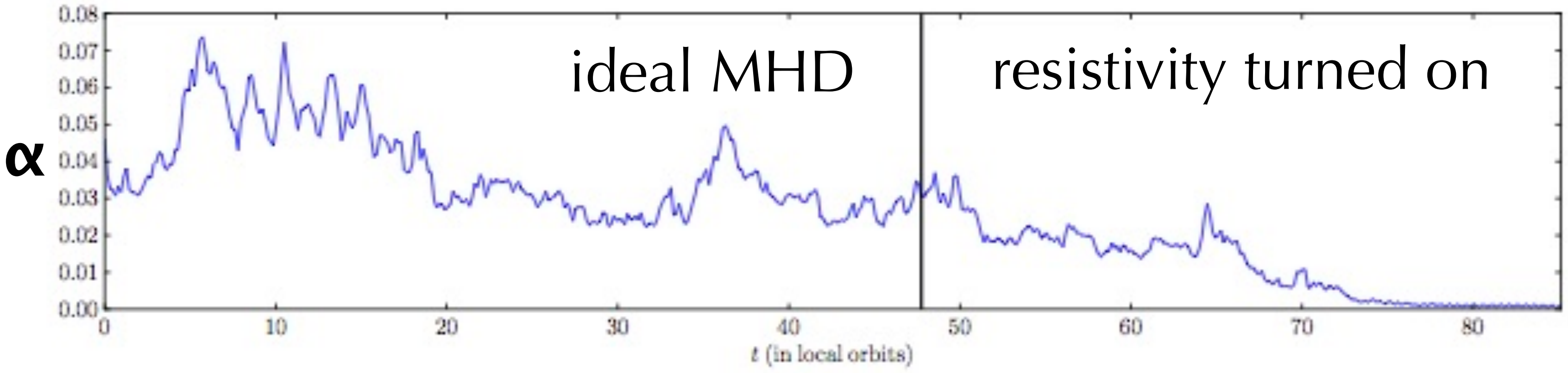
Increased α due to convection

Further evidence & non-ideal MHD sims

Scepi Lesur GD, submitted



- α is enhanced
- role of convection unclear
- resistivity (non-ideal MHD) quenches turbulence at low T (Gammie Menou 1998)

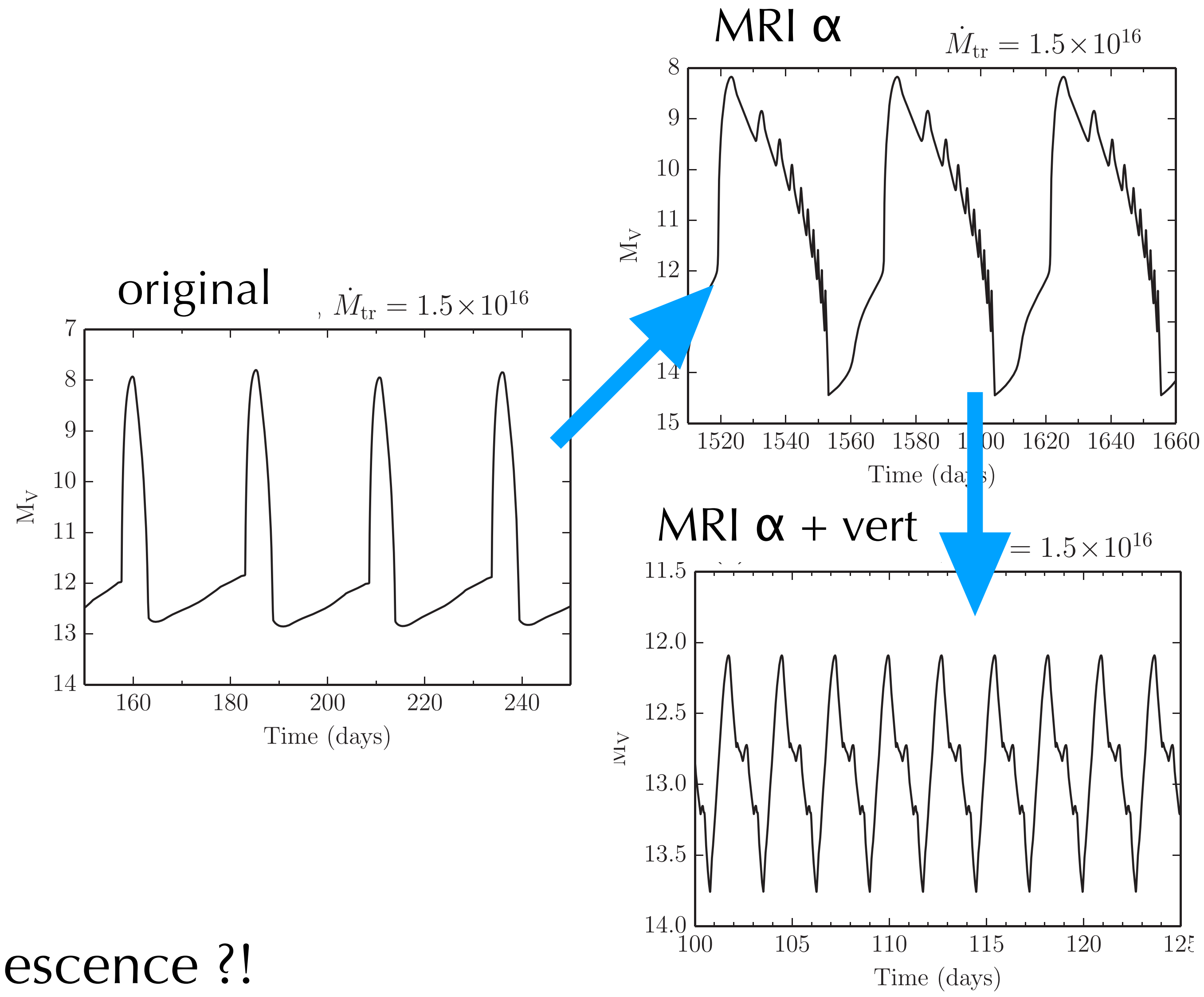


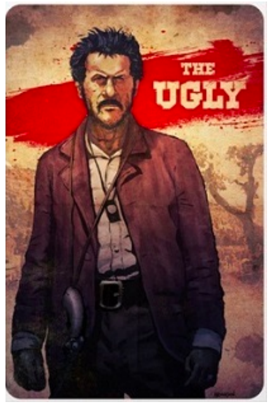
Time ⟶

The good, the bad, the ugly

Enhanced α connected to properties of MRI-driven turbulence

Lightcurves with α from MRI simulations don’t work well

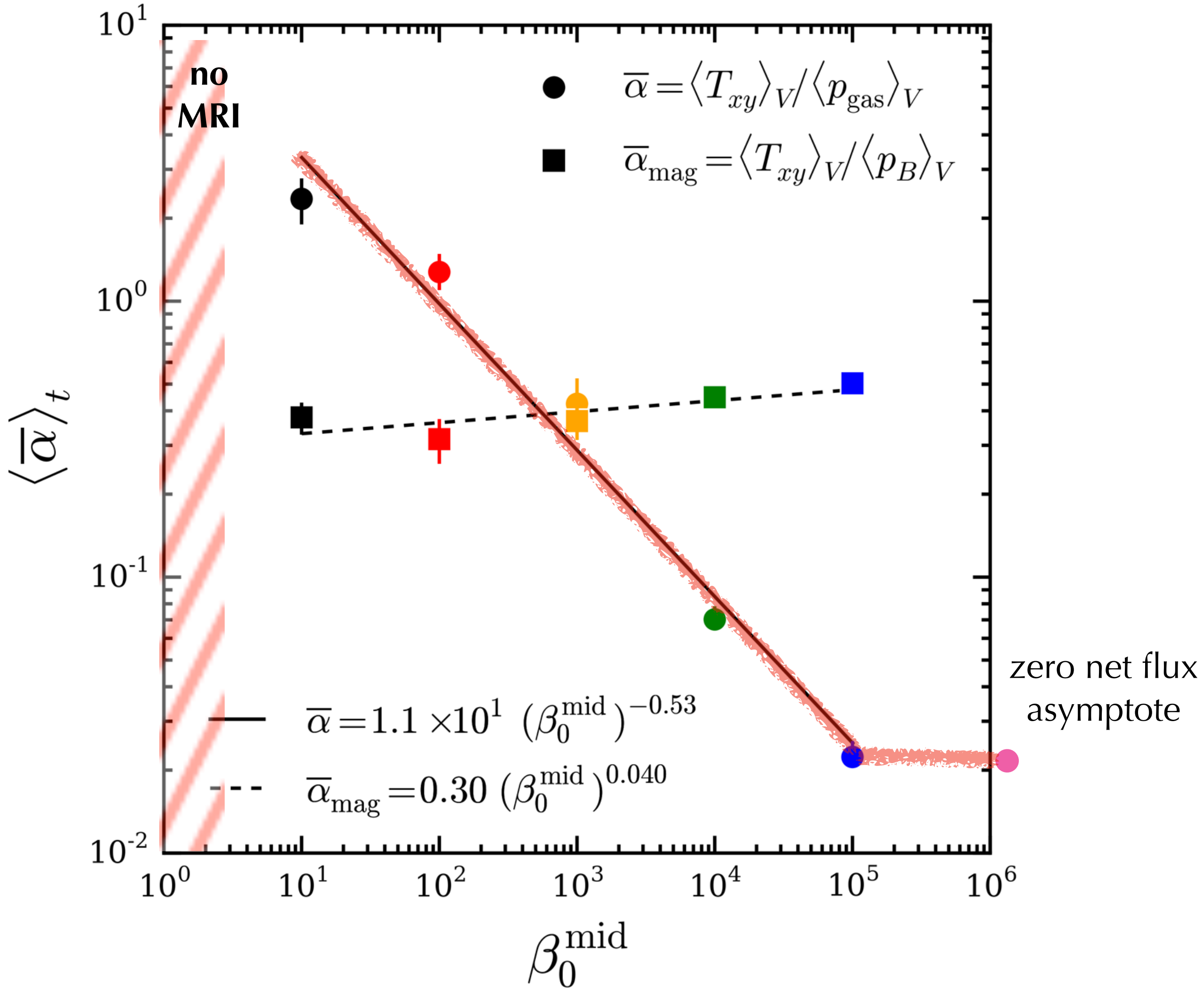




No MRI-driven transport in quiescence ?!

Coleman et al. 2015

Can a net vertical magnetic field help ?



zero net flux asymptote

Salvesen+ 2016

(1) **$\langle B_z \rangle \neq 0$** strongly enhances transport

(Hawley+1995)

$$\alpha \propto (P_0/B_0^2)^{-0.5}$$

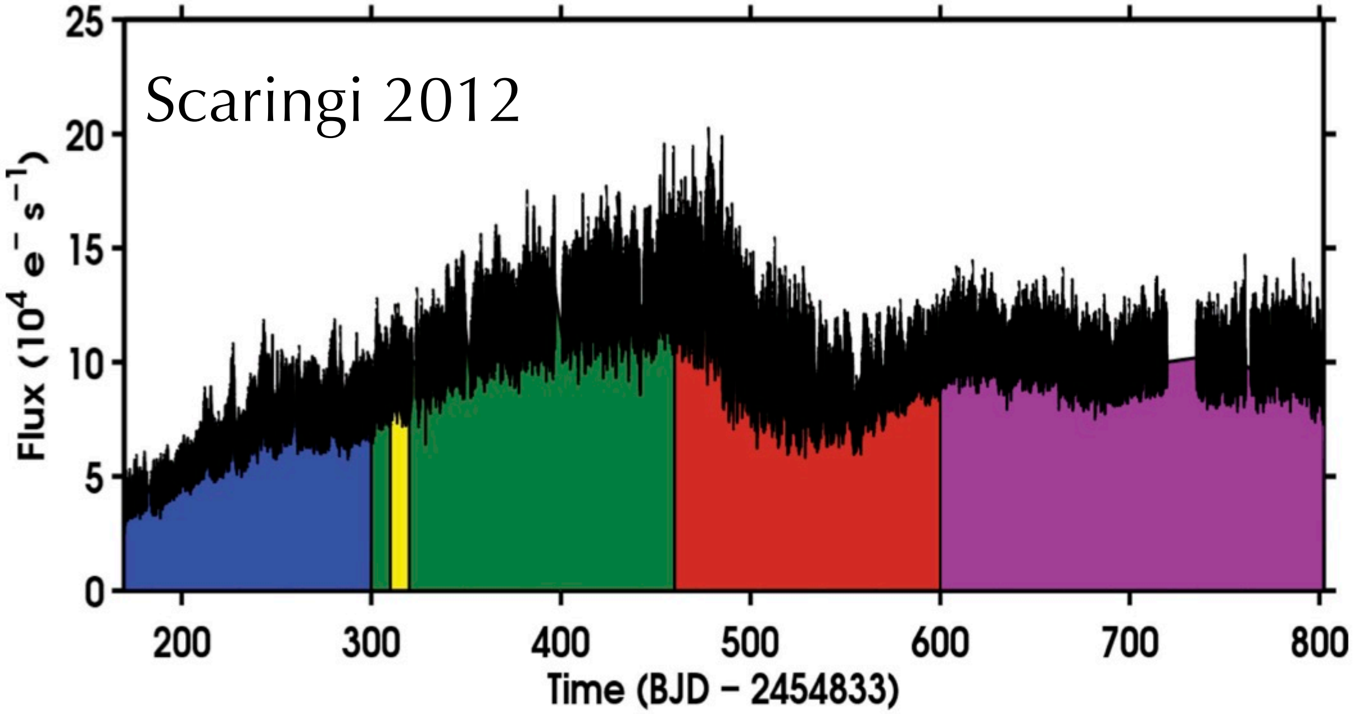
(2) may help sustain turbulence in quiescent branch (Fleming+ 2000)

(3) messy:

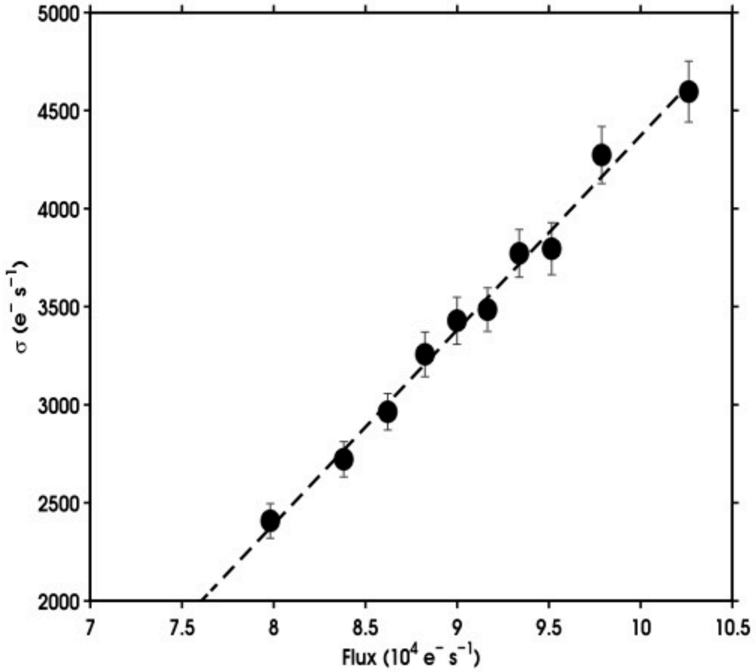
- origin & transport of $\langle B_z \rangle$?
- link to state changes ?
- large-scale outflows ?

Flickering in accreting objects

CV lightcurve (MV Lyr)



flux-rms (Uttley & McHardy 2001)

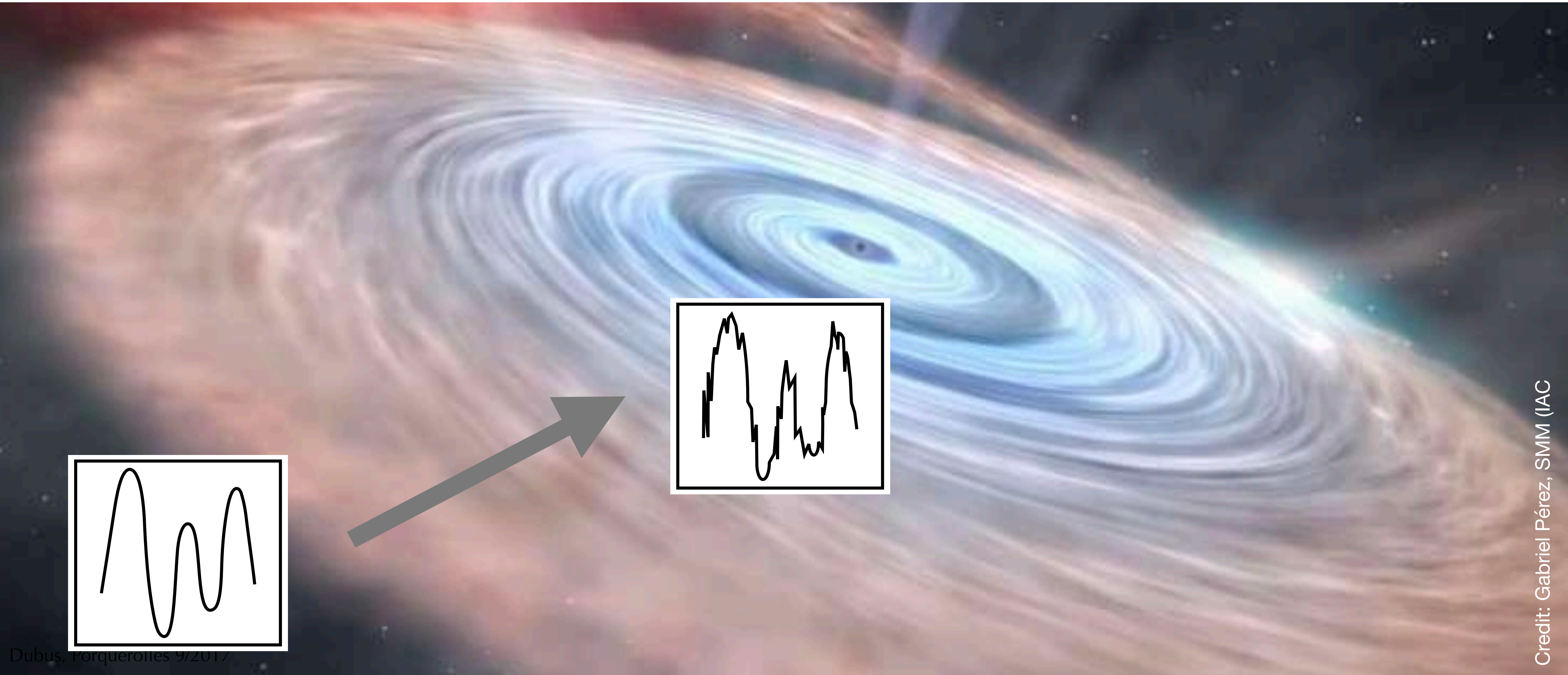


Propagating fluctuations

Accretion fluctuations propagate inward, modulated at faster timescales at smaller R

(Lyubarskii 1997)

MRI-driven fluctuations too fast ?



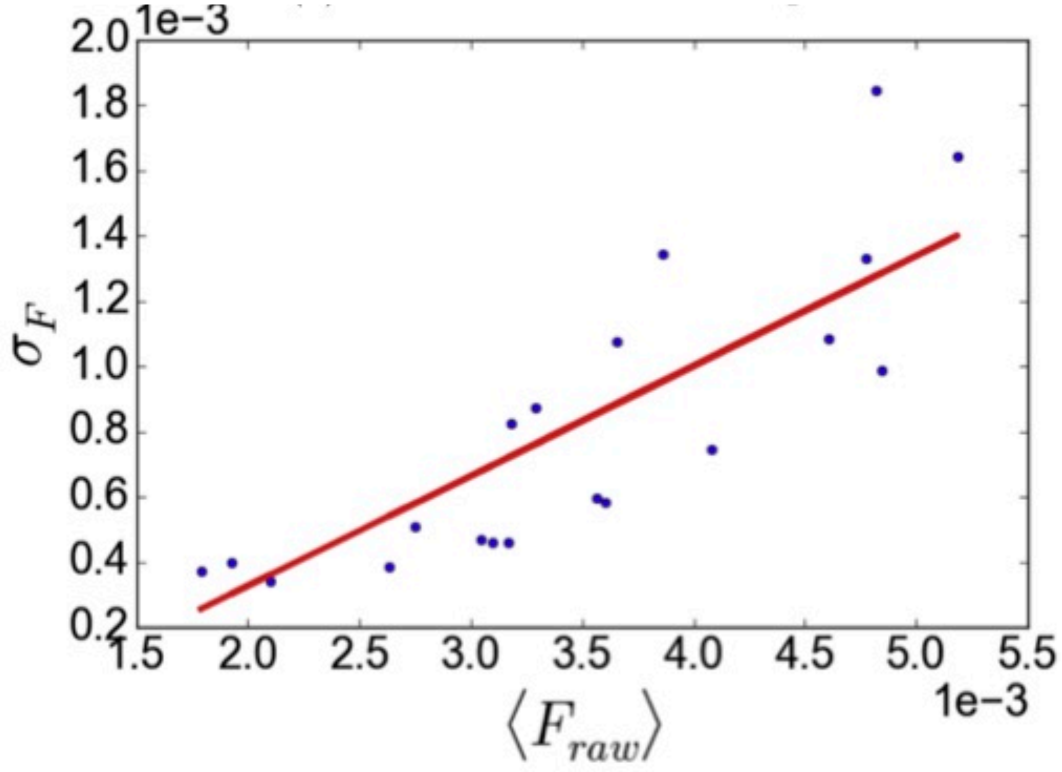
Credit: Gabriel Pérez, SMM (IAC

MRI-driven variability ?

Relevant timescale is MRI dynamo cycles (King+2004, Hogg & Reynolds 2016)

flux - rms from global MRI simulation

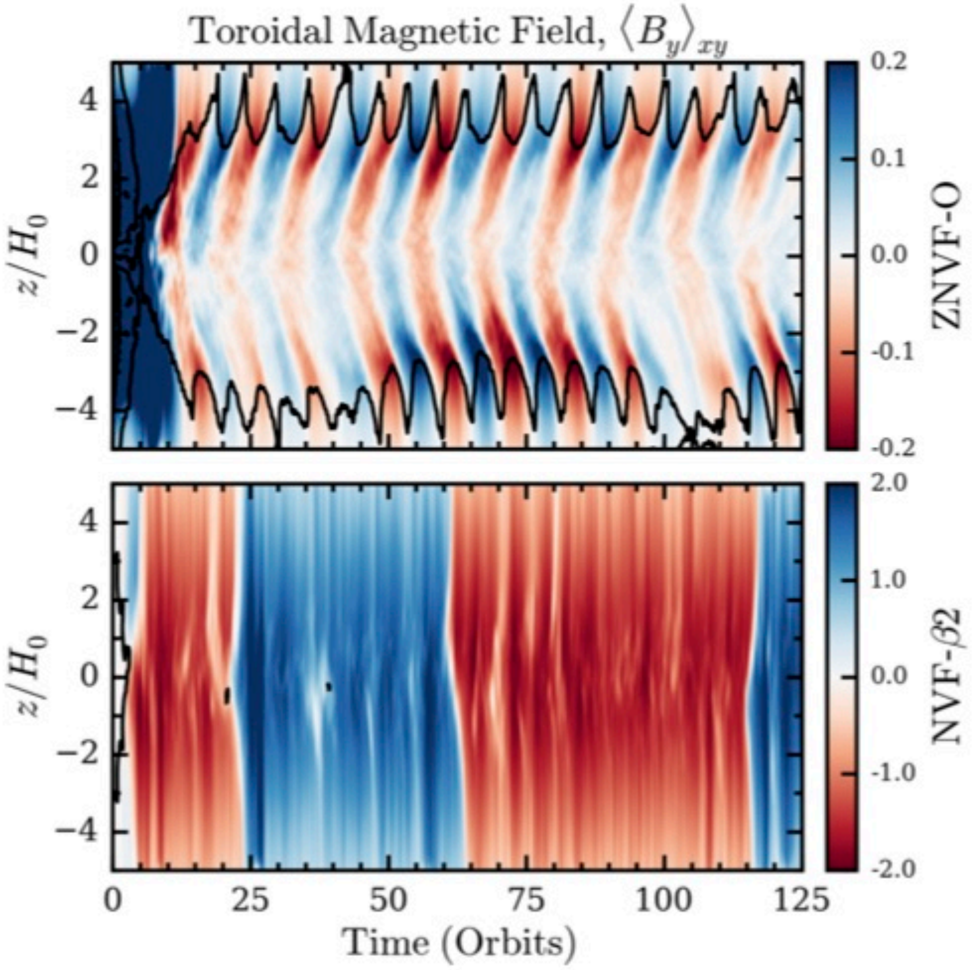
[NB disk has h/r~0.1]



Hogg & Reynolds 2016

toroidal field reversals associated to dynamo

(shearing box)



$<B_z>=0$

Salvesen+2017

$<B_z>\neq 0$

net flux, convection change dynamo timescale

Grand Unification Theory feelings

- **Scalings are puzzling**
- **Unification by analogy:** physical processes common to all objects
  - disk magnetosphere interaction
  - accretion flows
  - outflows & winds [?]
- **Many reasons for scalings to break**: radiation, microphysics, thermodynamics…
  - consequences can be key to interpret observations (e.g. disk instability model)
- **Progress** in connecting phenomenological models (& observations) with statistical properties of turbulence in disks from ab initio numerical simulations.