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Transport of angular momentum in magnetized disks of dwarf novae

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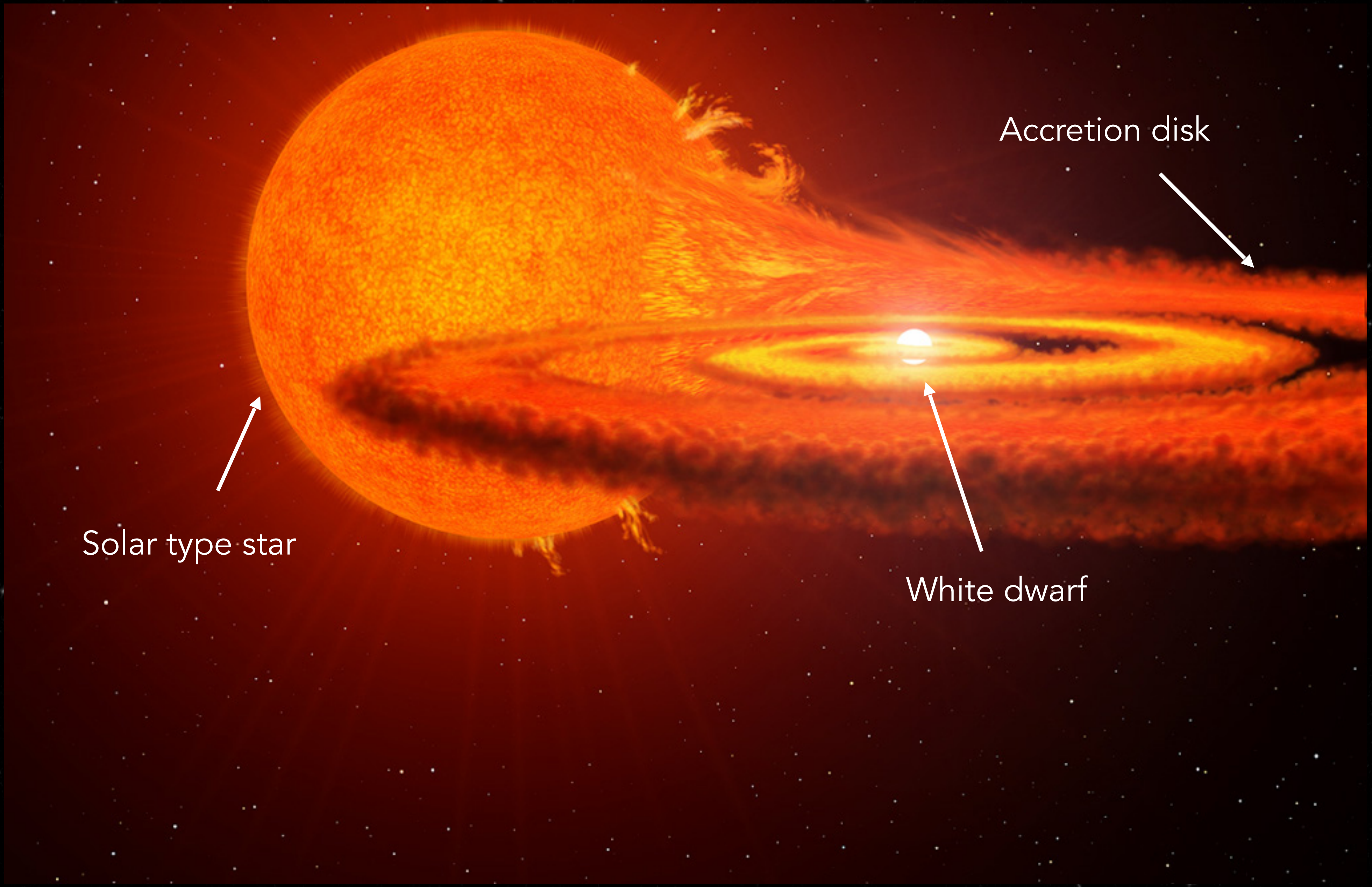
supervised by Guillaume Dubus and Geoffroy Lesur

PNHE, 1st of October 2018

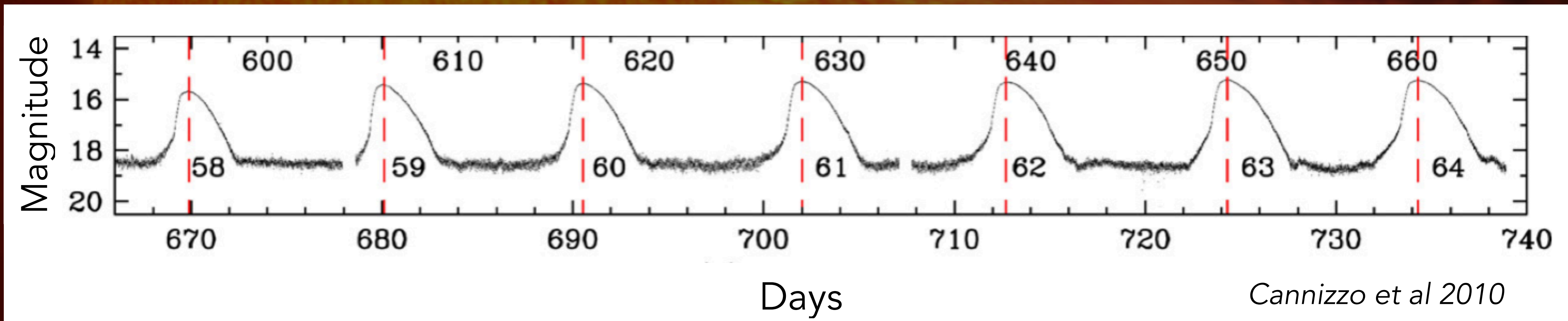
Dwarf novae



Dwarf novae are ideal to study accretion :

- emission in the visible, UV
- access to structure of the disk via eclipse mapping
- **high variability with time scales going from seconds to months**

Variability in dwarf novae (DNe)



Cannizzo et al 2010

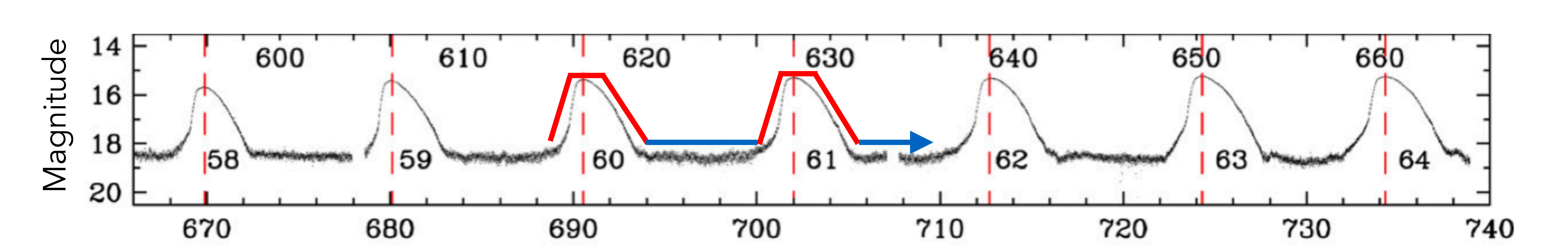
Luminosity coming from an α-disk

(Shakura & Sunyaev 1973)

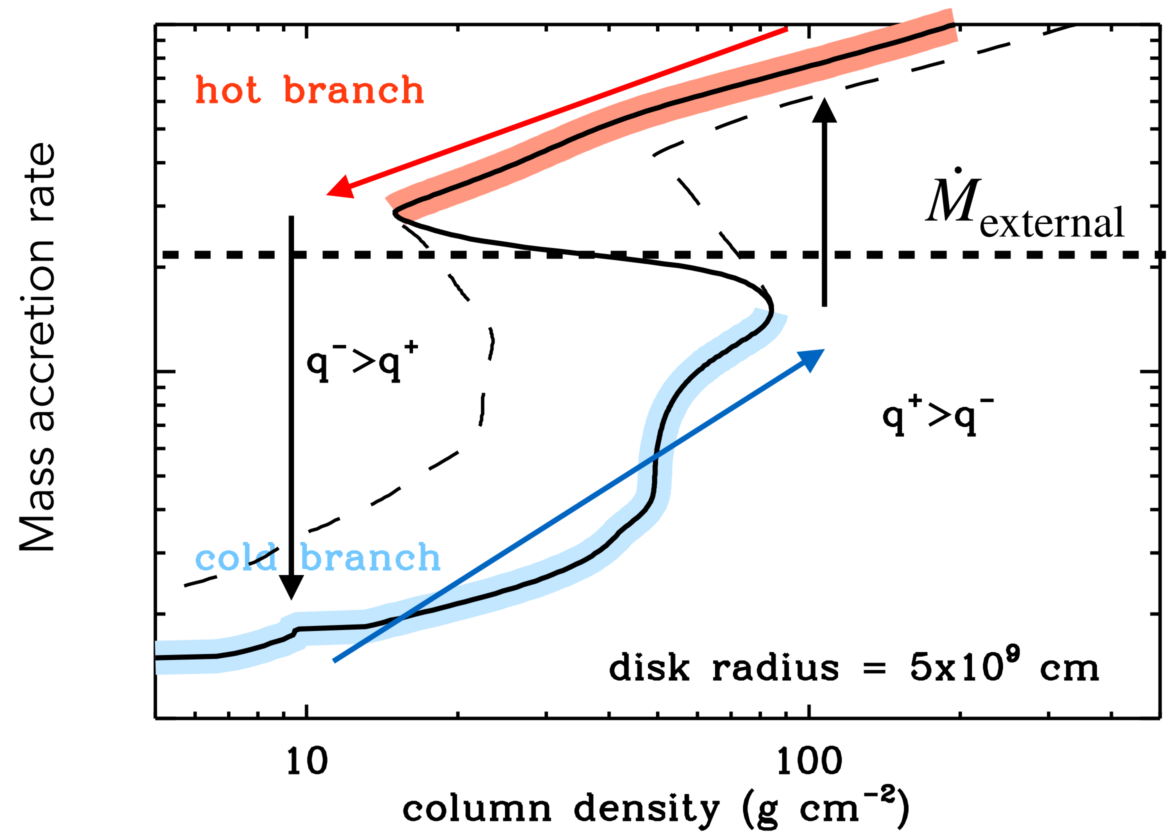
where turbulence is due to MRI.

(Balbus & Hawley 1991)

Disk instability model (DIM)



Cannizzo et al 2010



S-curve from the DIM

$$t_{\rm vis} = \frac{1}{\alpha\Omega}\left(\frac{R}{H}\right)^2 \qquad t_{\rm therm} = \frac{1}{\alpha\Omega}$$

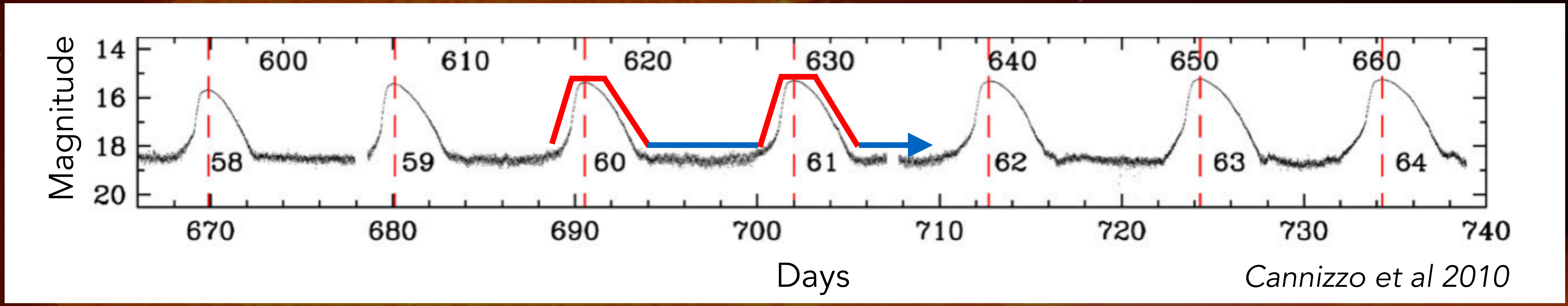
Eruptive state $\alpha \sim 0.1$

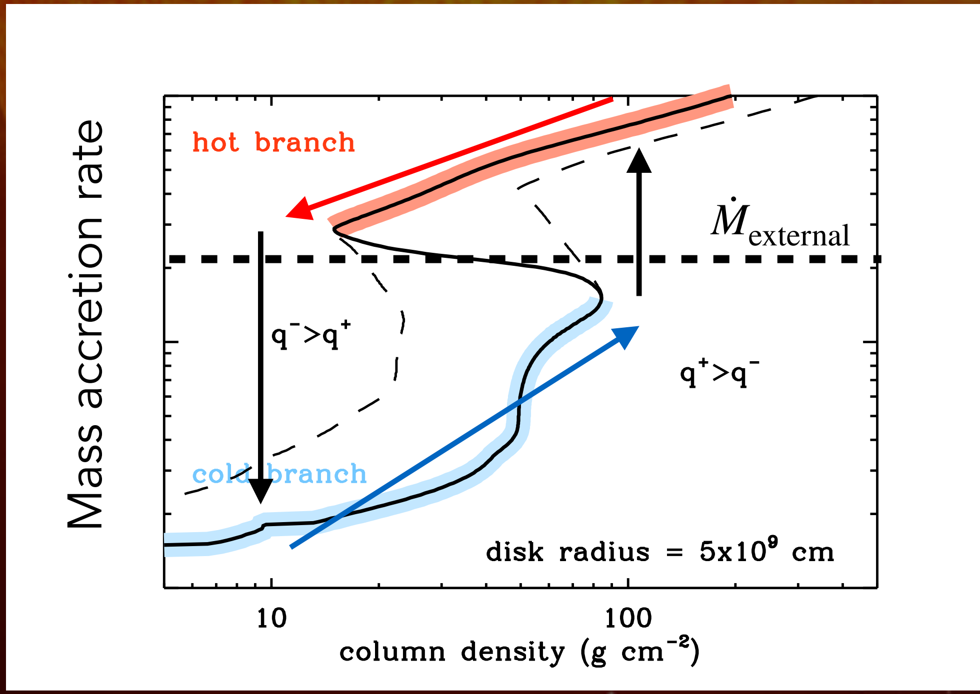
(Kotko & Lasota 2012)

Quiescent state $\alpha \sim 0.01$

(Cannizzo et al. 2012)

Disk instability model (DIM)





S-curve from the DIM

$$t_{\rm vis} = \frac{1}{\alpha\Omega}\left(\frac{R}{H}\right)^2 \qquad t_{\rm therm} = \frac{1}{\alpha\Omega}$$

Eruptive state α ~ 0.1

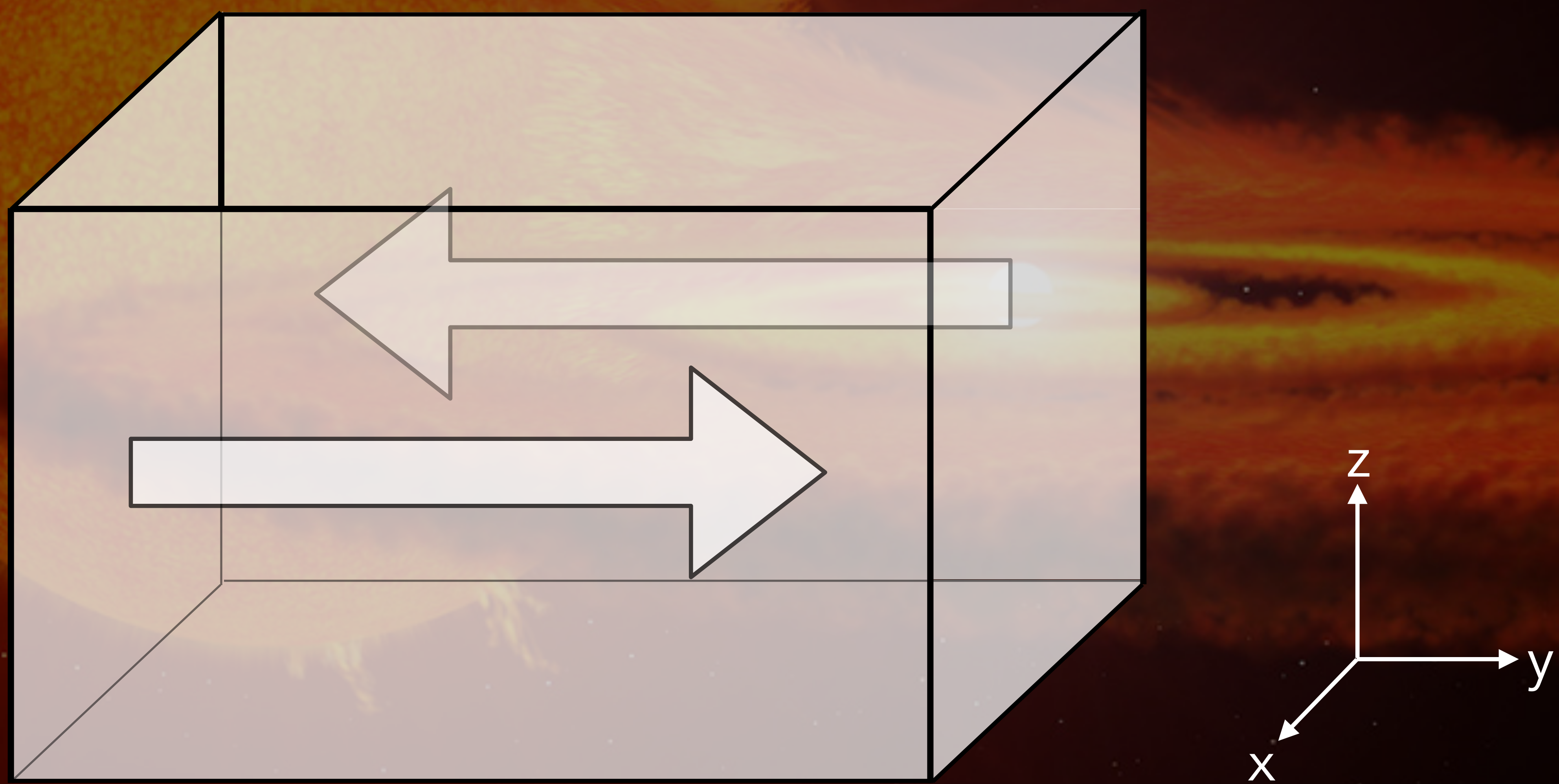
(Kotko & Lasota 2012)

Quiescent state α ~ 0.01

(Cannizzo et al. 2012)

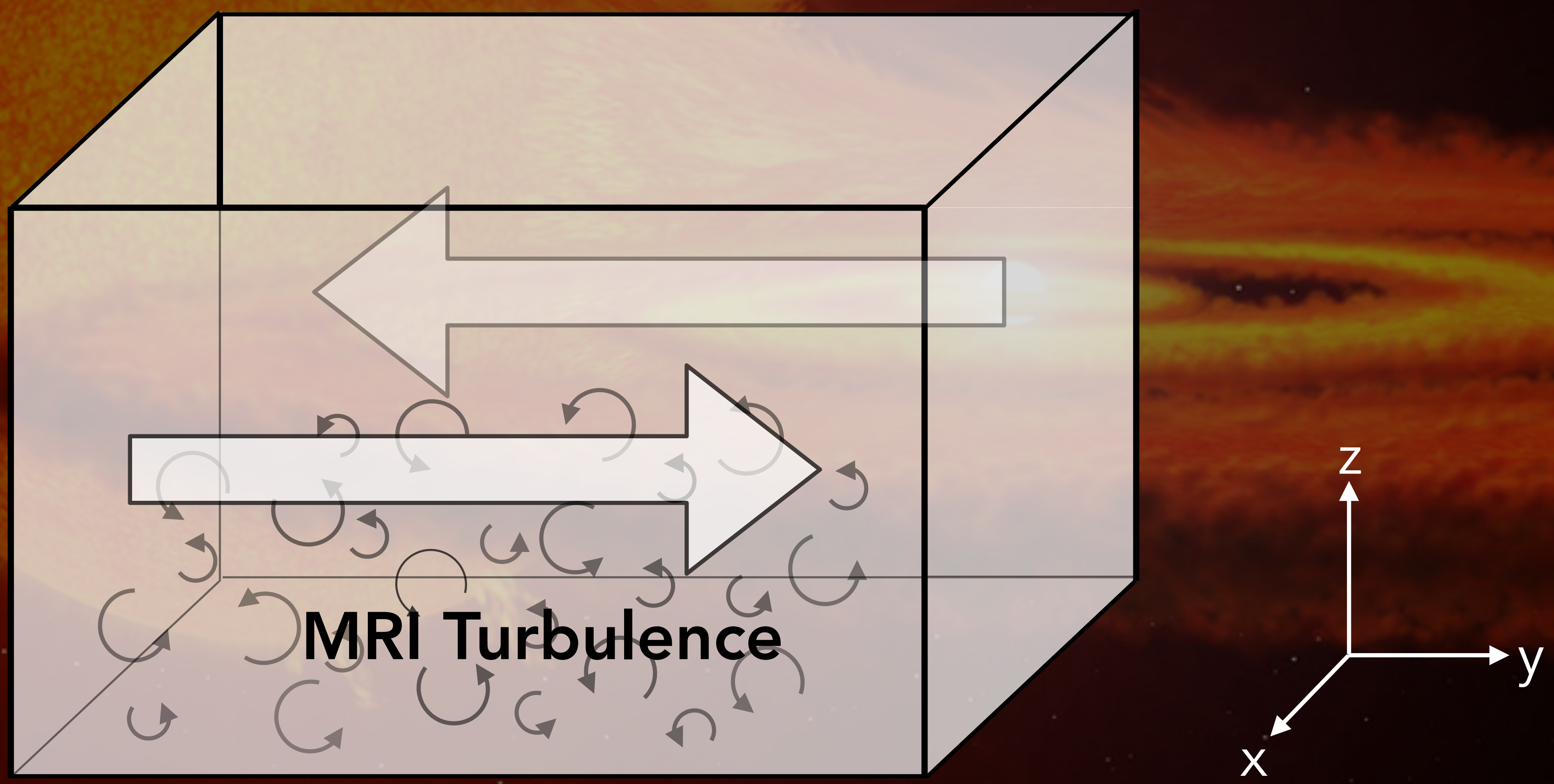
Can MRI explain the behavior of DNe?

General method



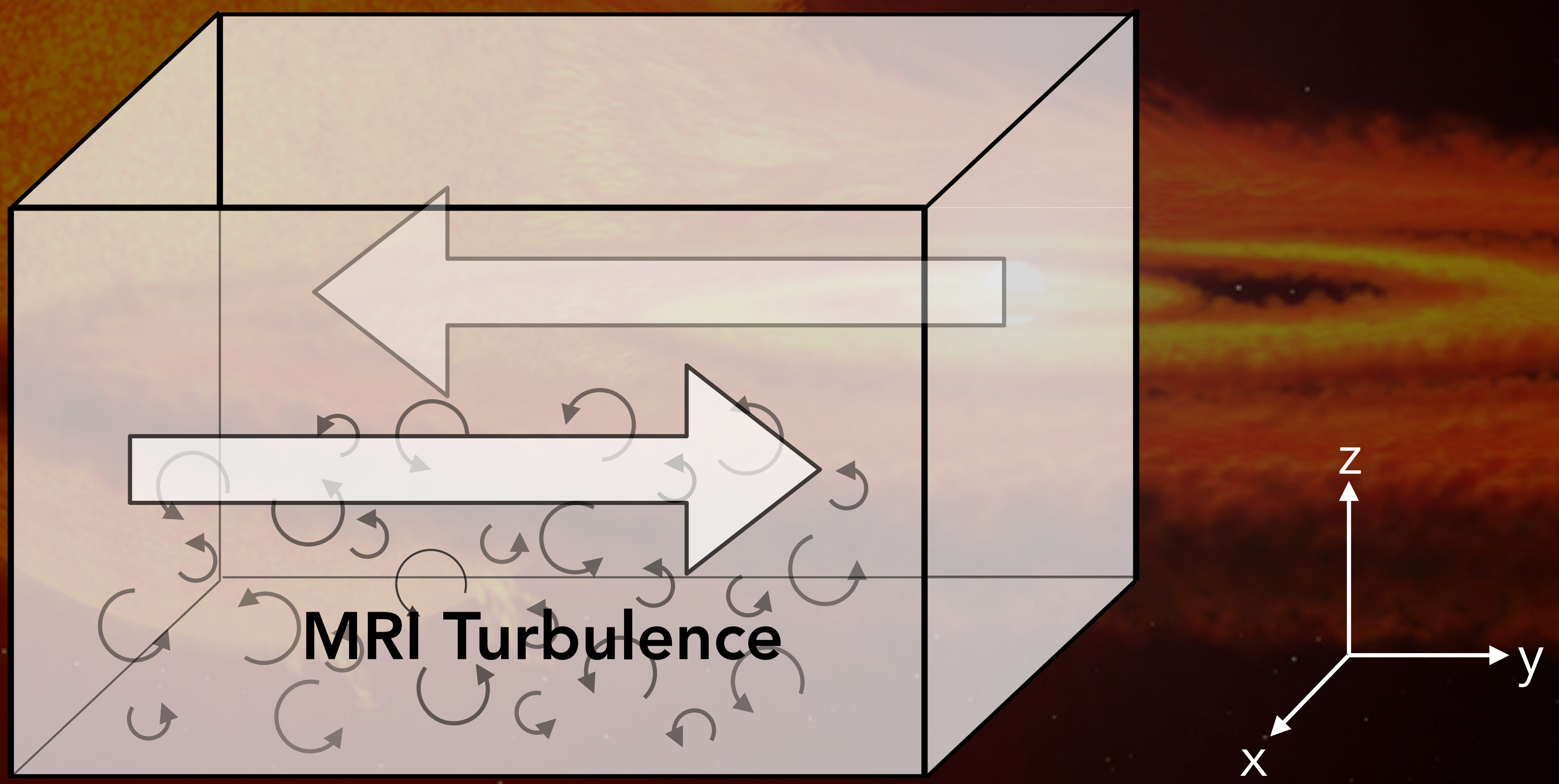
Local shearing box

General method



Local shearing box

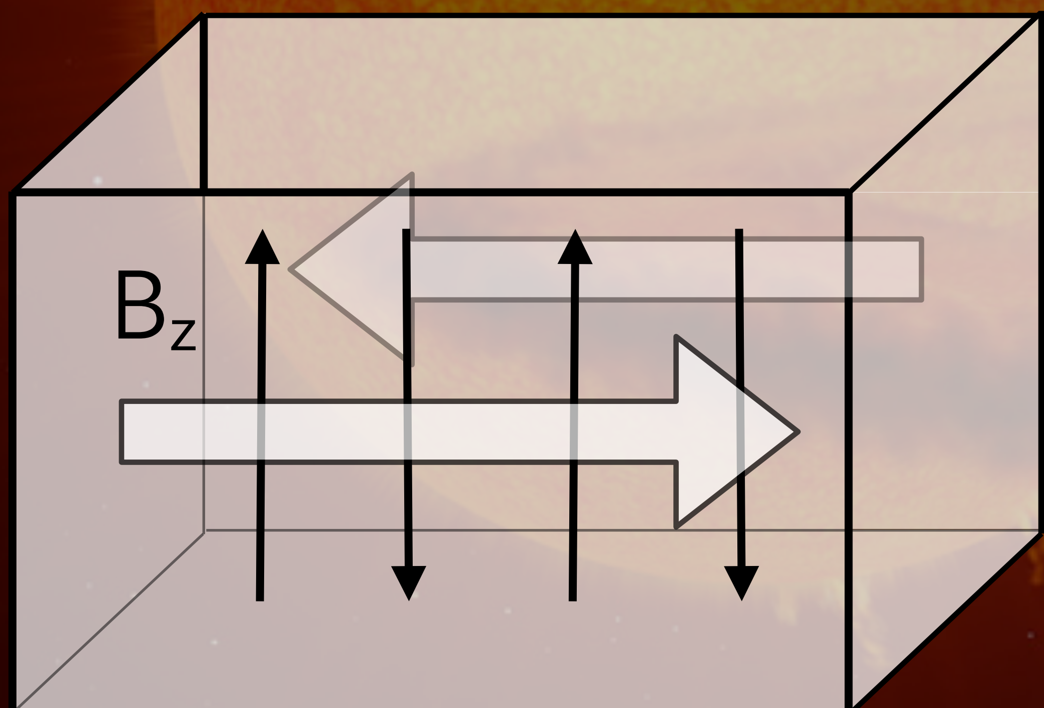
General method



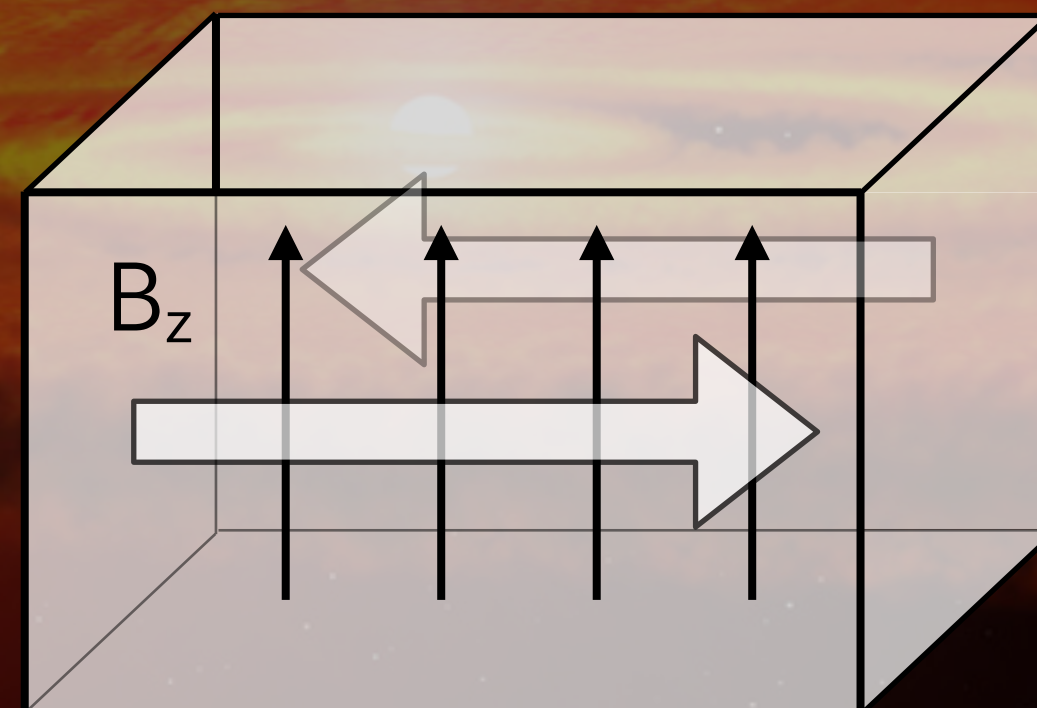
Local shearing box

Compute α !!

Magnetic configuration



Zero net flux



Net flux

Brief review of ZNF MRI simulations

Isothermal, prescribed cooling:

α ~ 0.01

(*Hawley et al. 1996, Simon et al. 2012, Latter & Papaloizou 2012*)

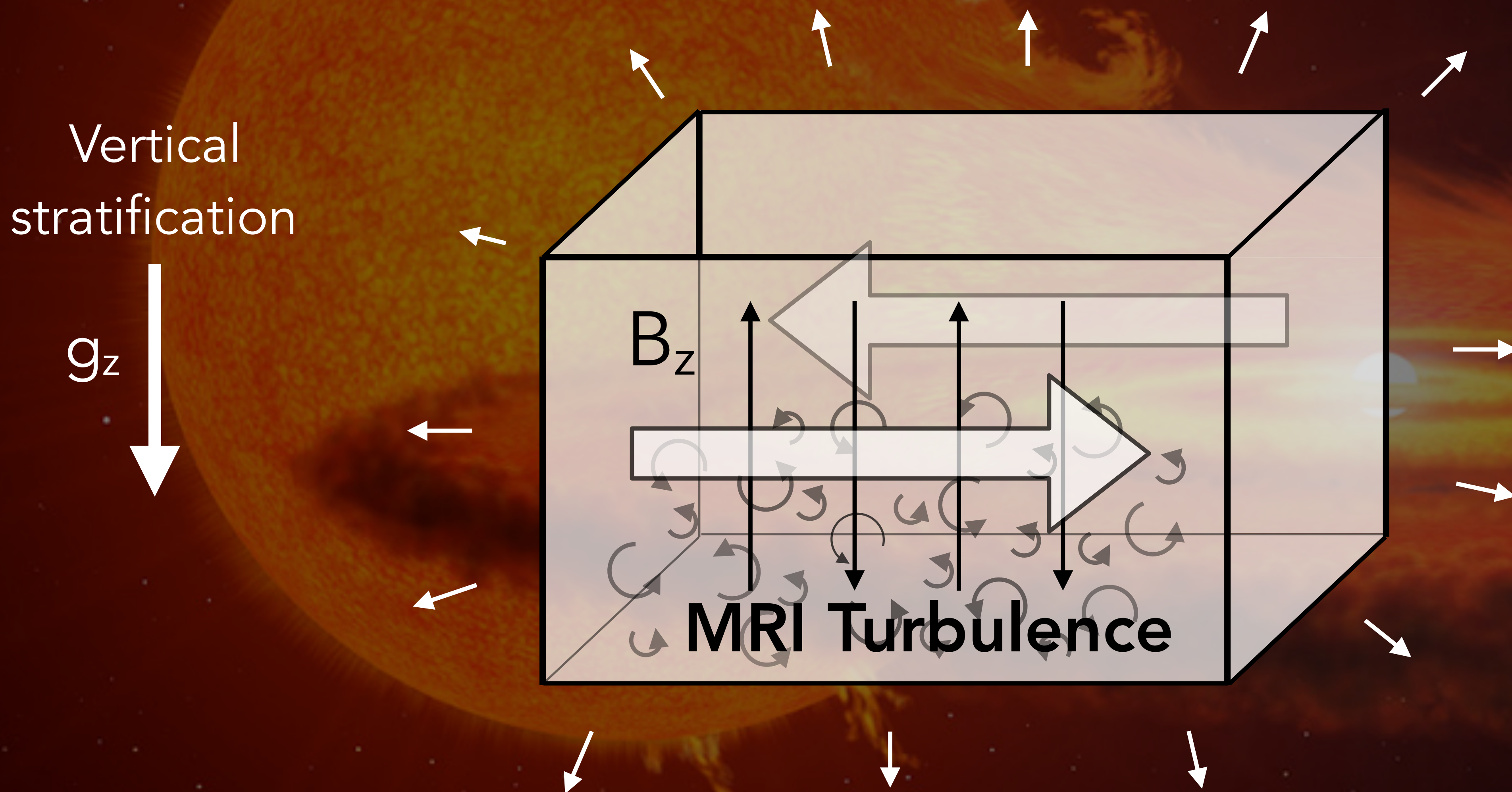
Radiative transfer and realistic thermodynamic, stratified :

α ~ 0.03 on the cold branch

α ~ 0.1 on the hot branch near hydrogen ionization regime

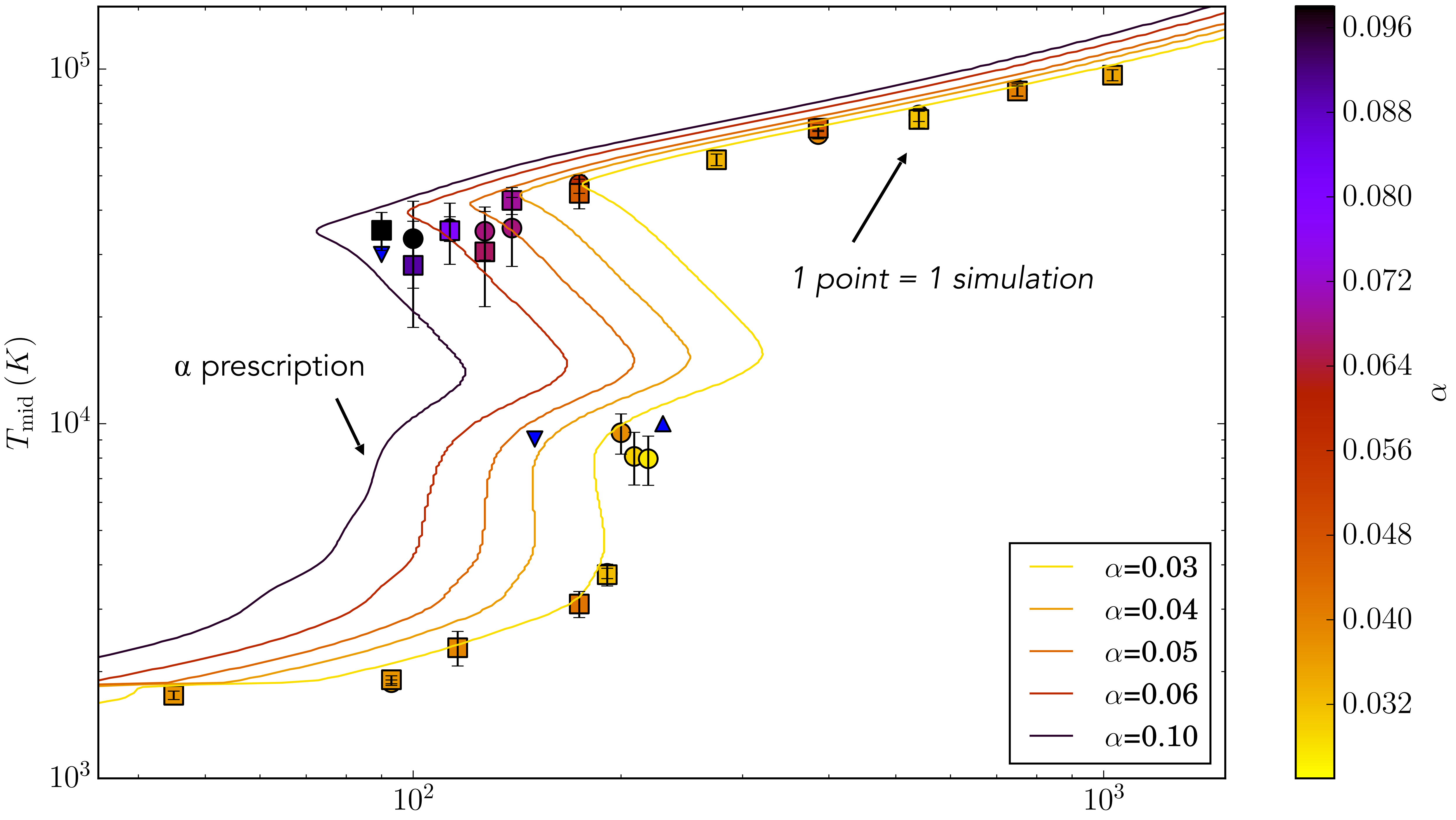
(Hirose et al. 2014)

Motivations



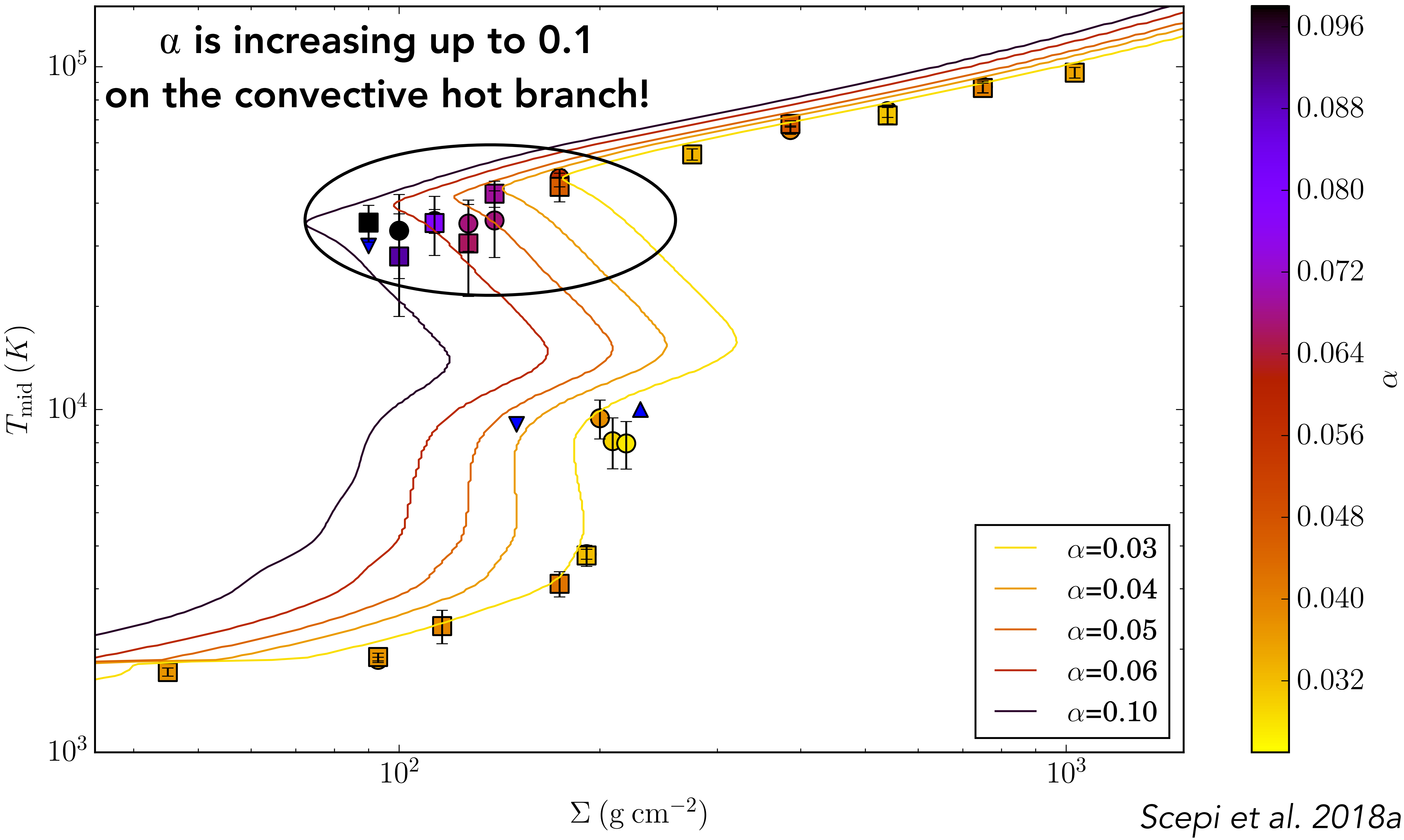
- Retrieve α~0.1 on the hot branch with another code (PLUTO), different boundary conditions
- Add resistivity on the cold branch *(Gammie & Menou 1998)*

Equilibrium curves with ZNF



Scepi et al. 2018a

Enhancement of α



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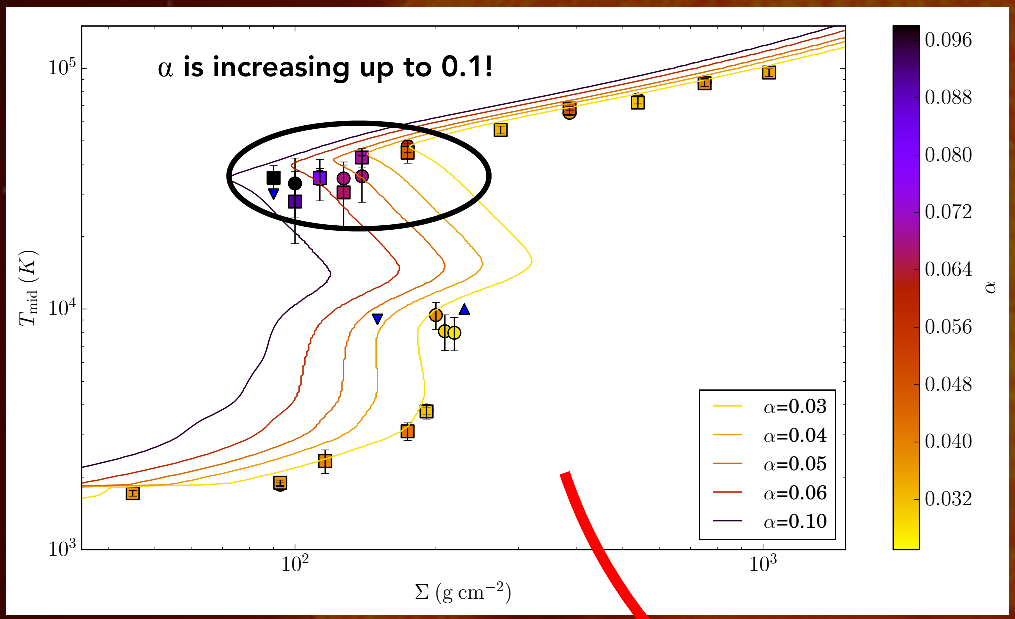
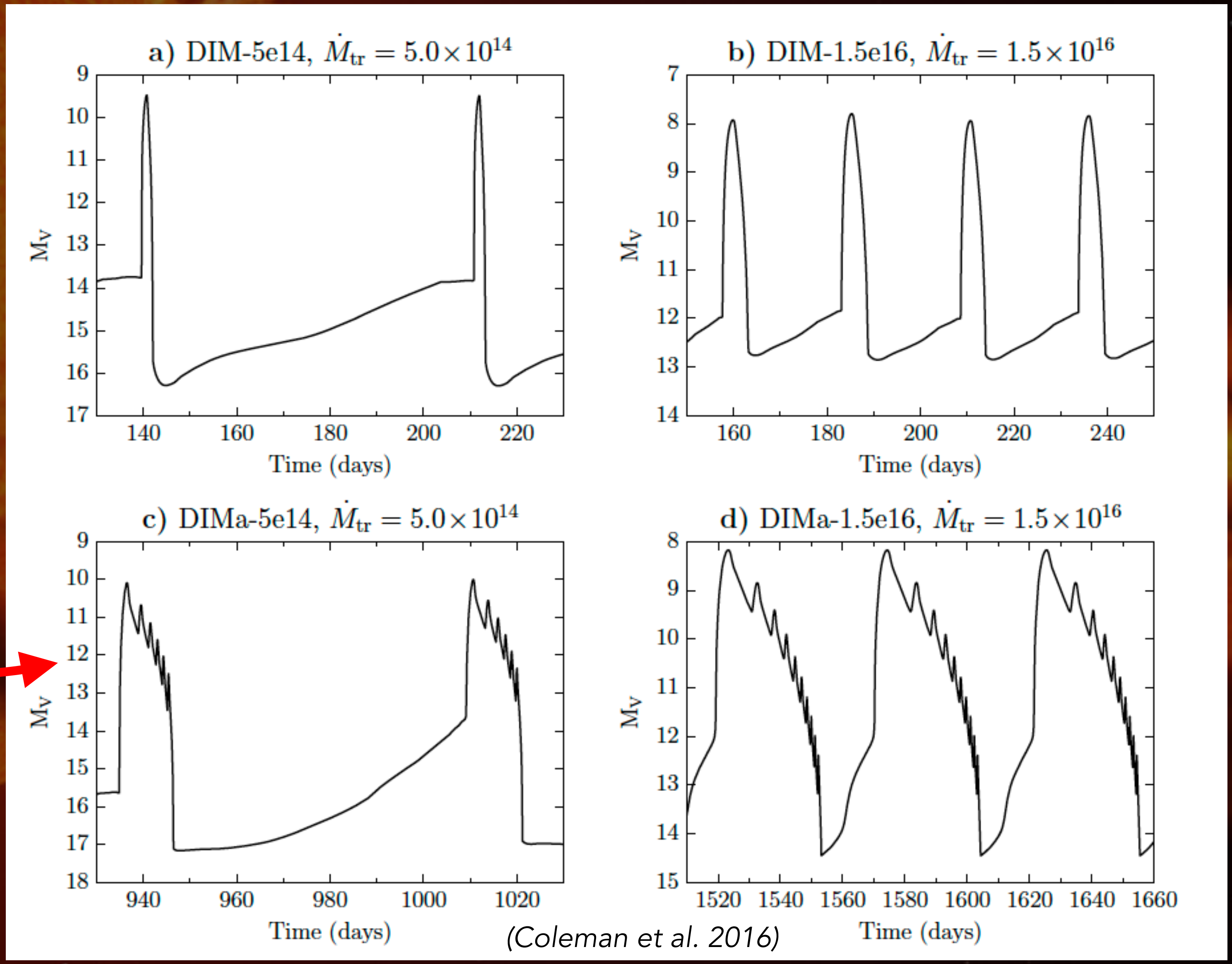
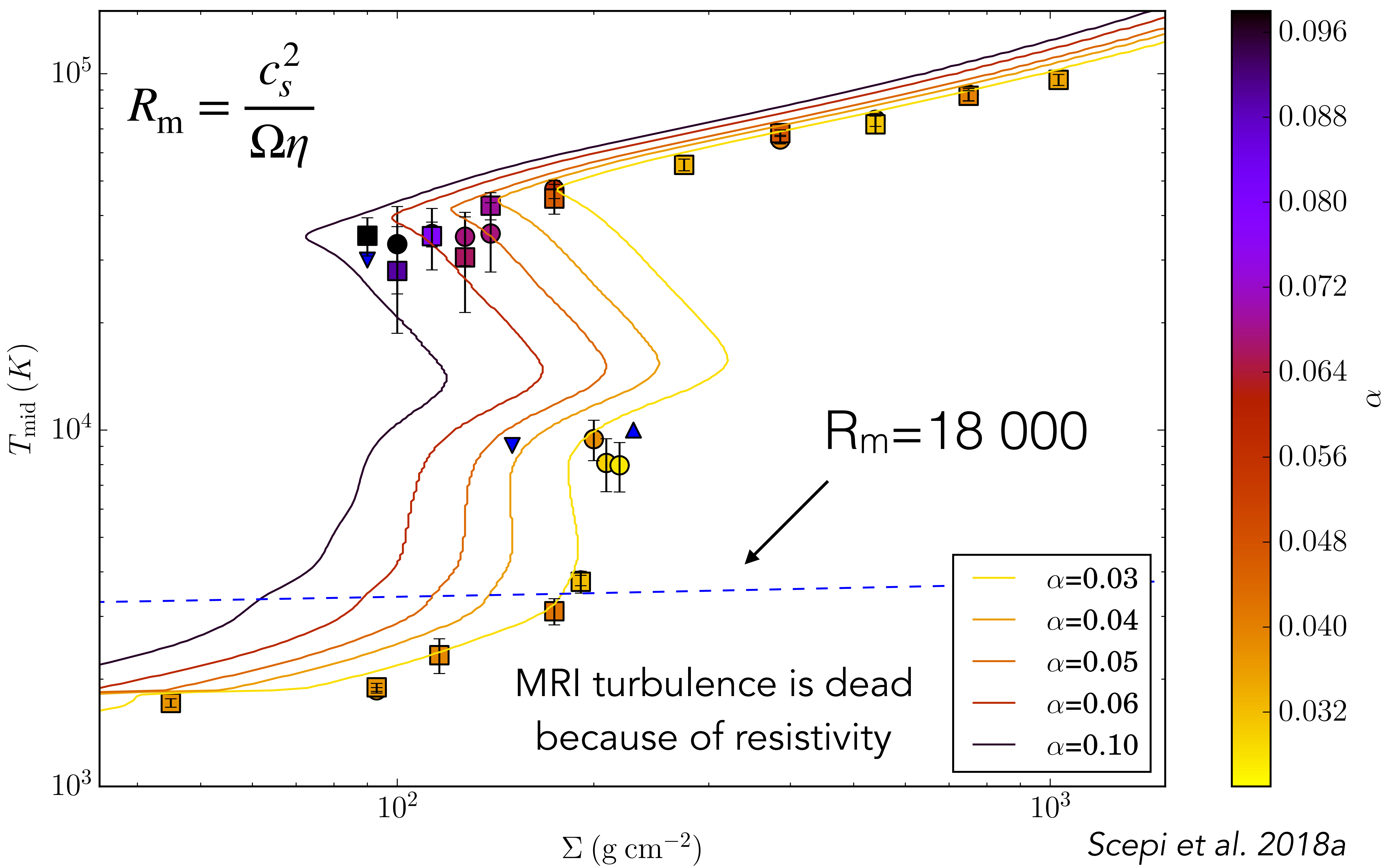




Cannot explain the light curves !

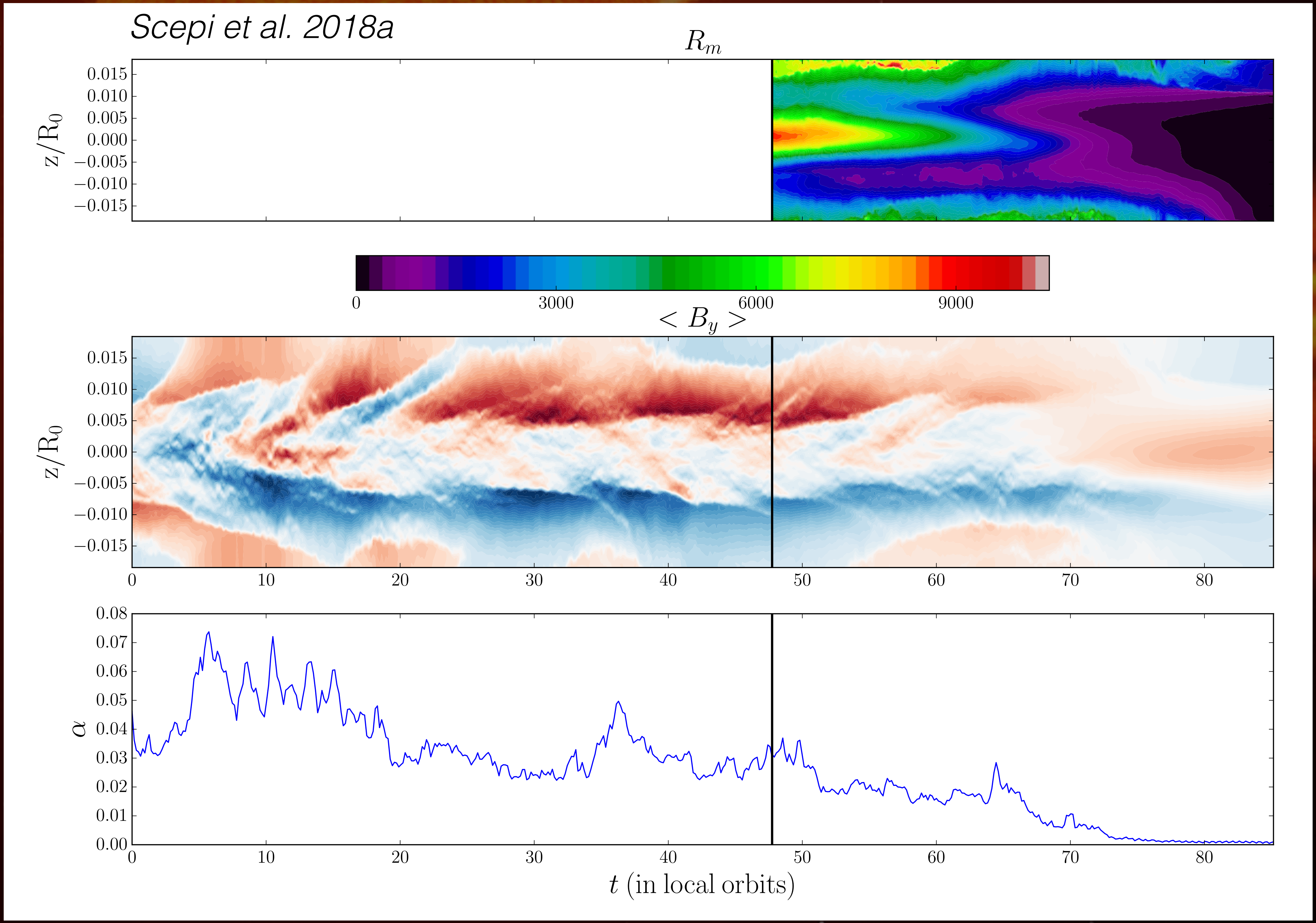
(Coleman et al. 2016)

Resistive cold branch



Scepi et al. 2018a

Resistive cold branch

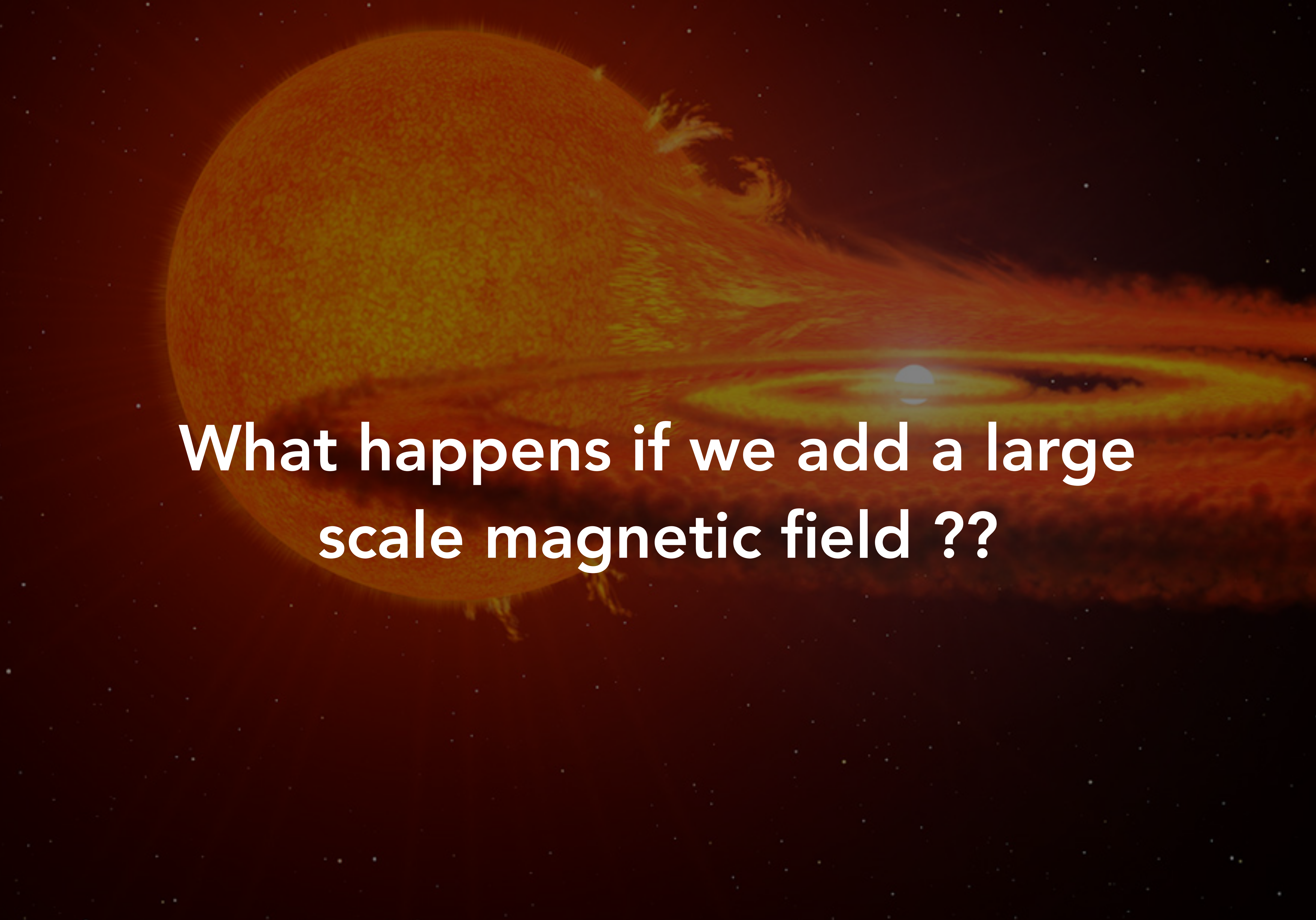


Conclusion for zero net flux simulations

α ~ 0.1 near the tip of the hot branch!
However, this does not reproduce the light curves
(Coleman et al. 2016)

When we include resistivity MRI is quenched on the cold branch *(as predicted by Gammie & Menou 1998)***.**

Yet, there is observational evidence that DNe in quiescence accrete *(Mukai et al 2013).*



What happens if we add a large scale magnetic field ??

What happens if we add a large scale magnetic field ??

$$\beta = \frac{8\pi P_{thermal}}{< B_z >^2}$$

$$\alpha \propto \beta^{-0.5}$$

(Hawley et al. 1995)

α~0.1 on the hot branch only requires the right magnetization

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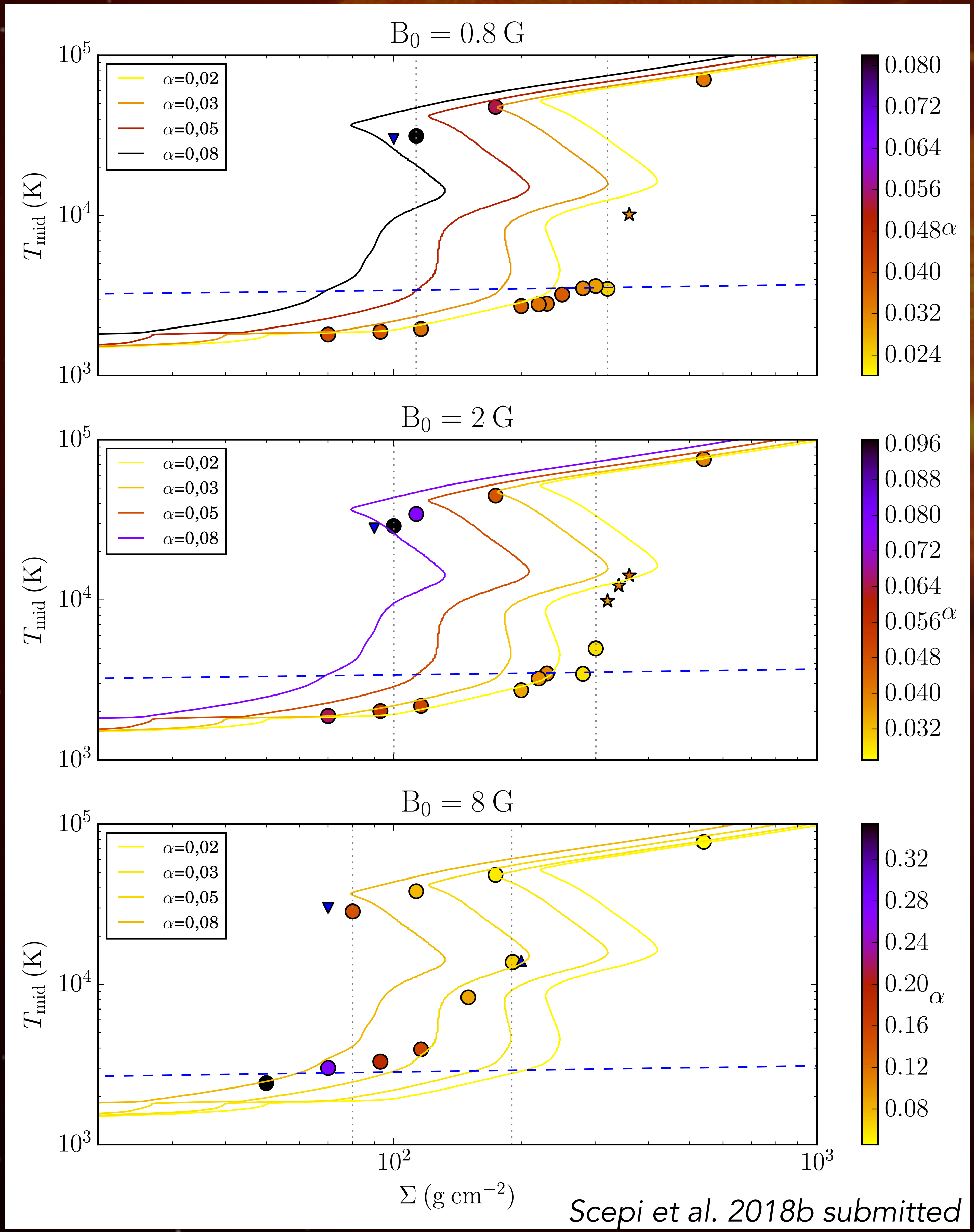
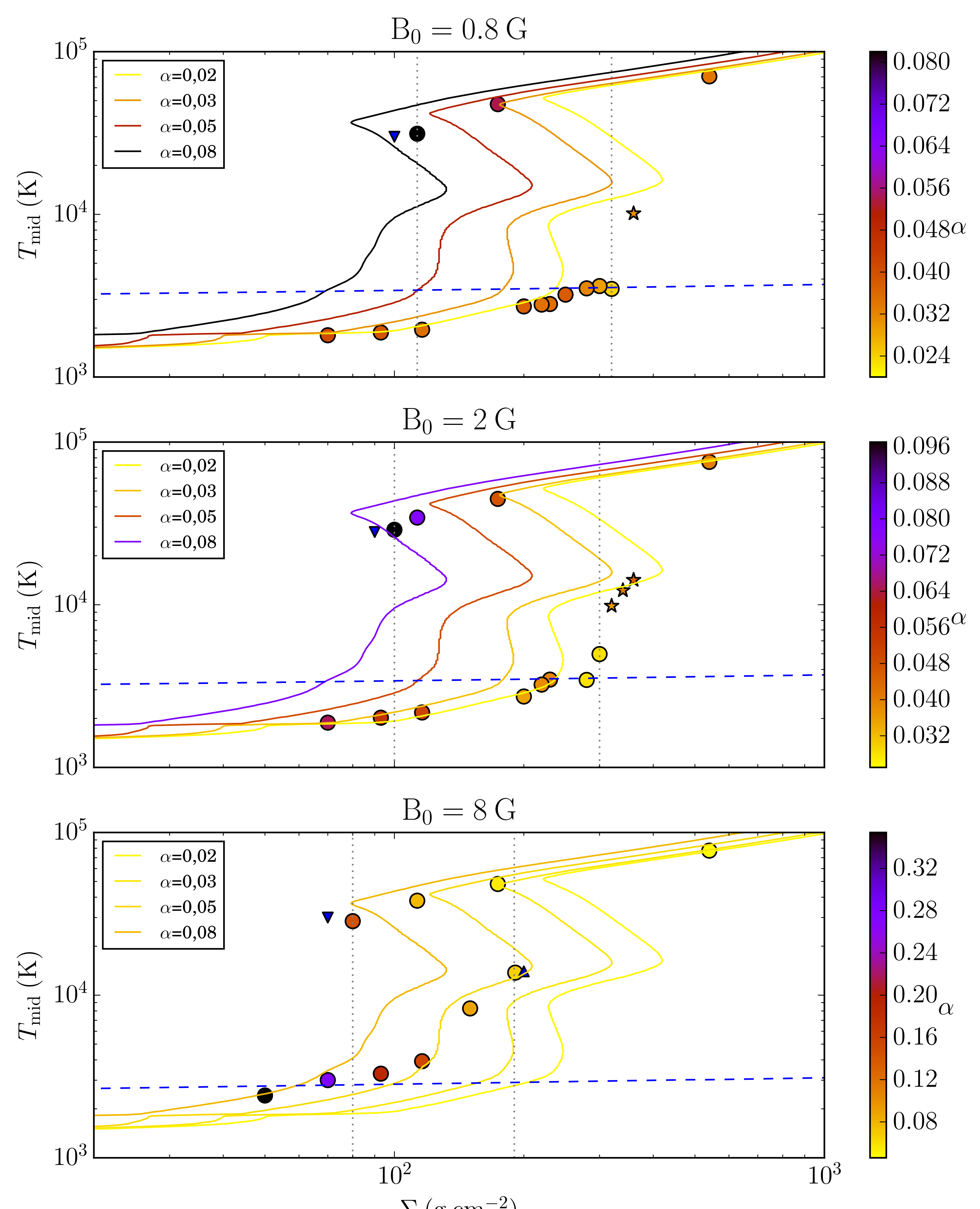
MRI turbulence goes to lower ionizations with net magnetic fields
(Fleming et al. 2000)

Equilibrium curves with net flux



- As we increase B_z, agreement with the DIM worsens.

Equilibrium curves with net flux



Scepi et al. 2018b submitted

- As we increase B_z, agreement with the DIM worsens.
- Since magnetic configuration unknown, we use a constant B_z.

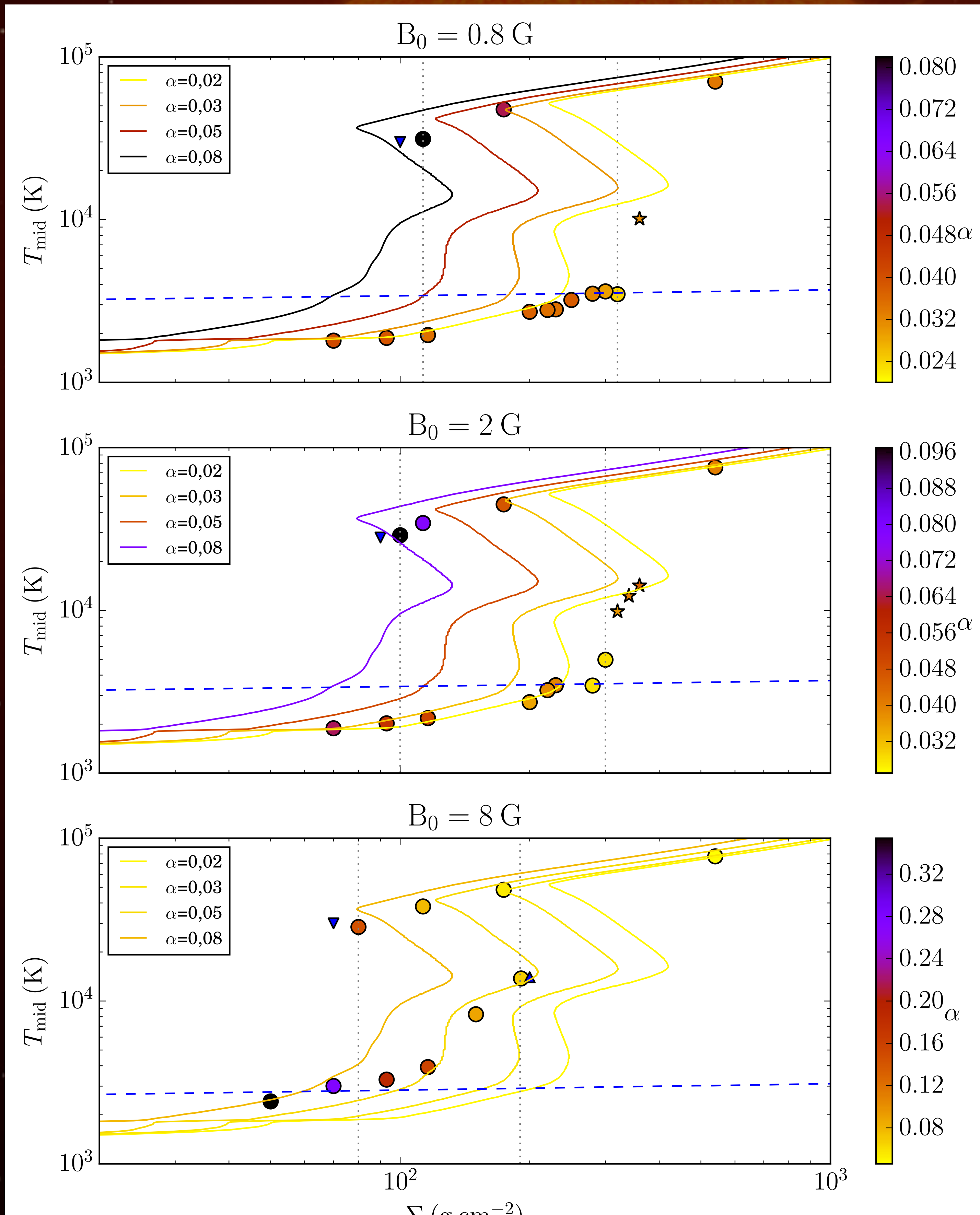
⇓

$$\beta_{cold} < \beta_{hot}$$

⇓

$\alpha_{cold} > \alpha_{hot}$ for $B_z > 2$ G

Equilibrium curves with net flux



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⇓

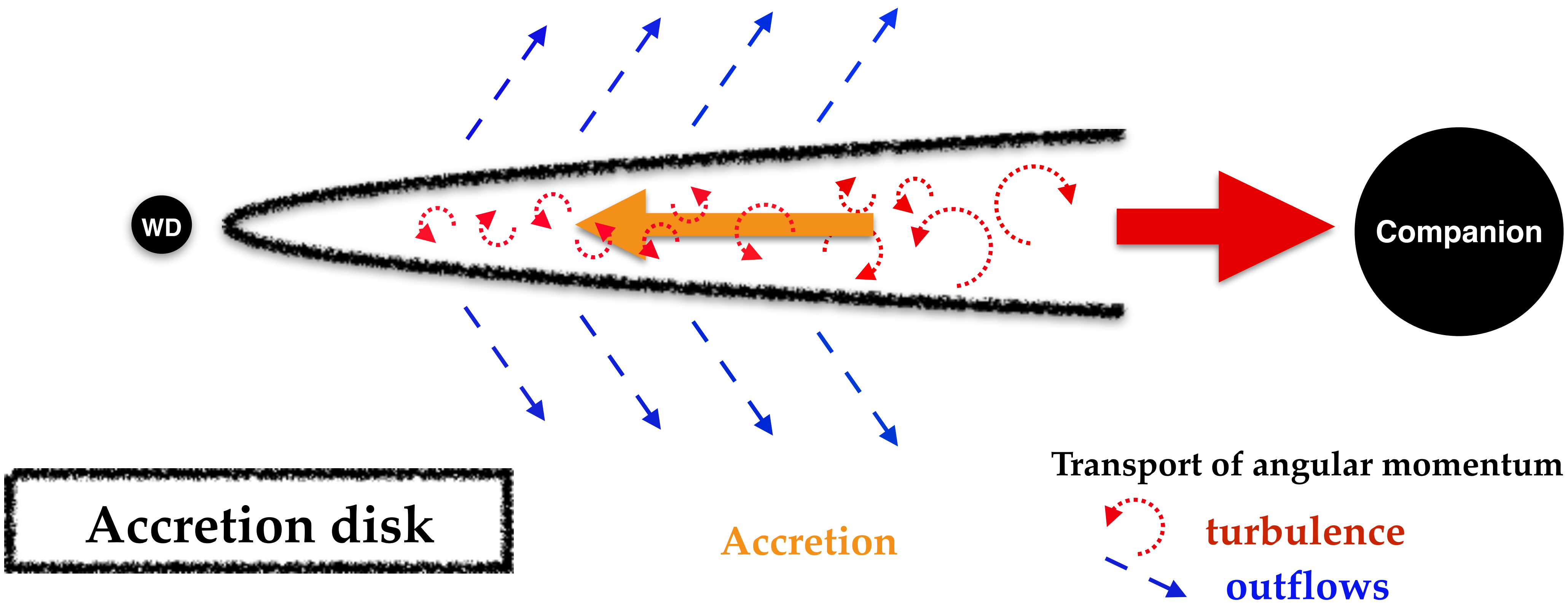
$$\beta_{cold} < \beta_{hot}$$

⇓

$\alpha_{cold} > \alpha_{hot}$ for $B_z > 2$ G

- **When B_z>2G, cold branch survives to lower densities but $\alpha > 0.1$!**

Outflows



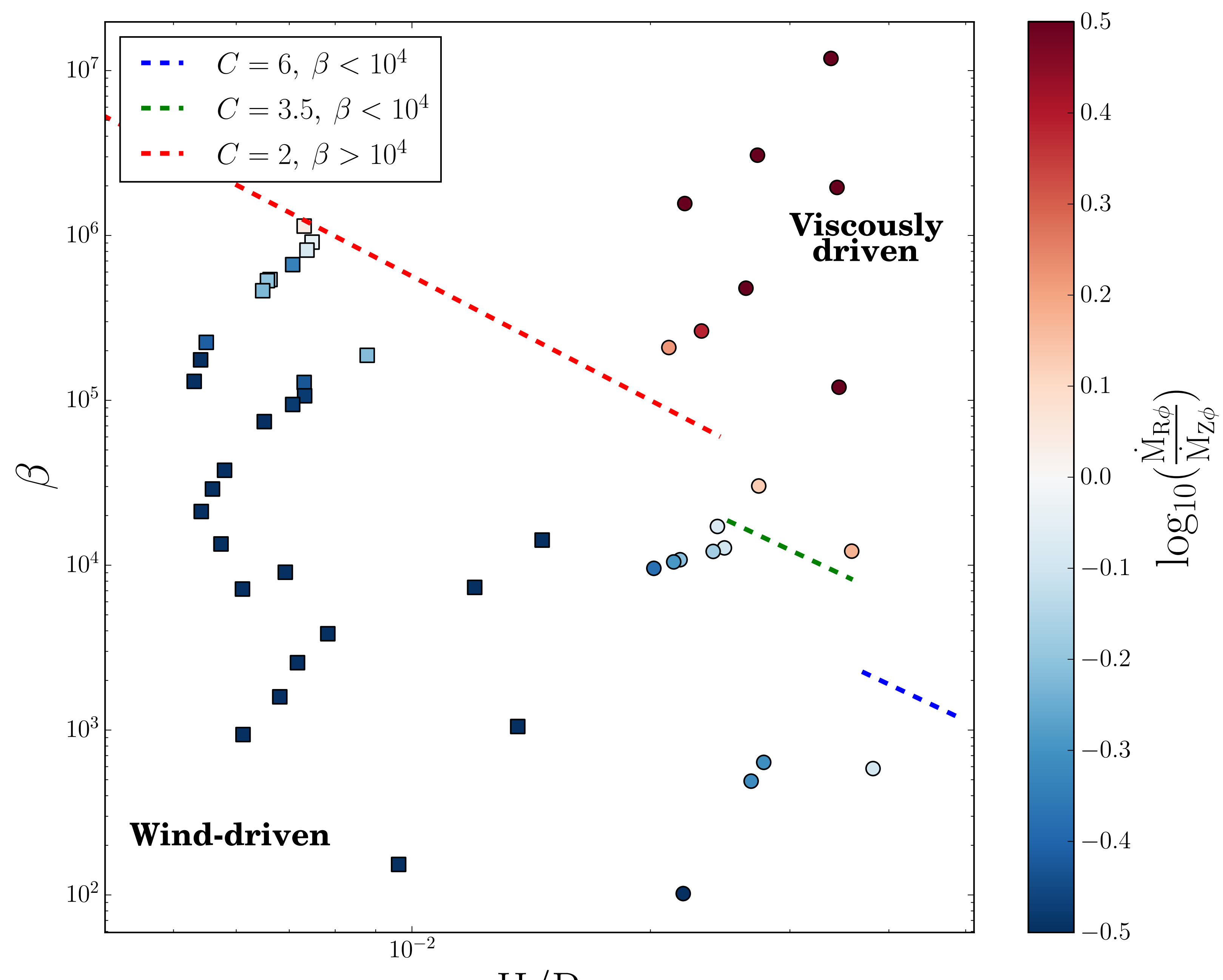
$$\Sigma \langle u_R \rangle_\rho = -\frac{1}{(R^2\Omega)'}\left(\underbrace{\frac{1}{R}\partial_R(\Sigma R^2 W_{R\phi})} + \underbrace{[\Sigma R W_{z\phi}]^{\mathrm{up}}_{\mathrm{down}}}\right)$$

$$\dot{M} = \dot{M}_{R\phi} + \dot{M}_{z\phi}$$

Mass accretion rate due to turbulent transport.

Mass accretion rate due to wind-driven transport.

Turbulent VS wind-driven accretion

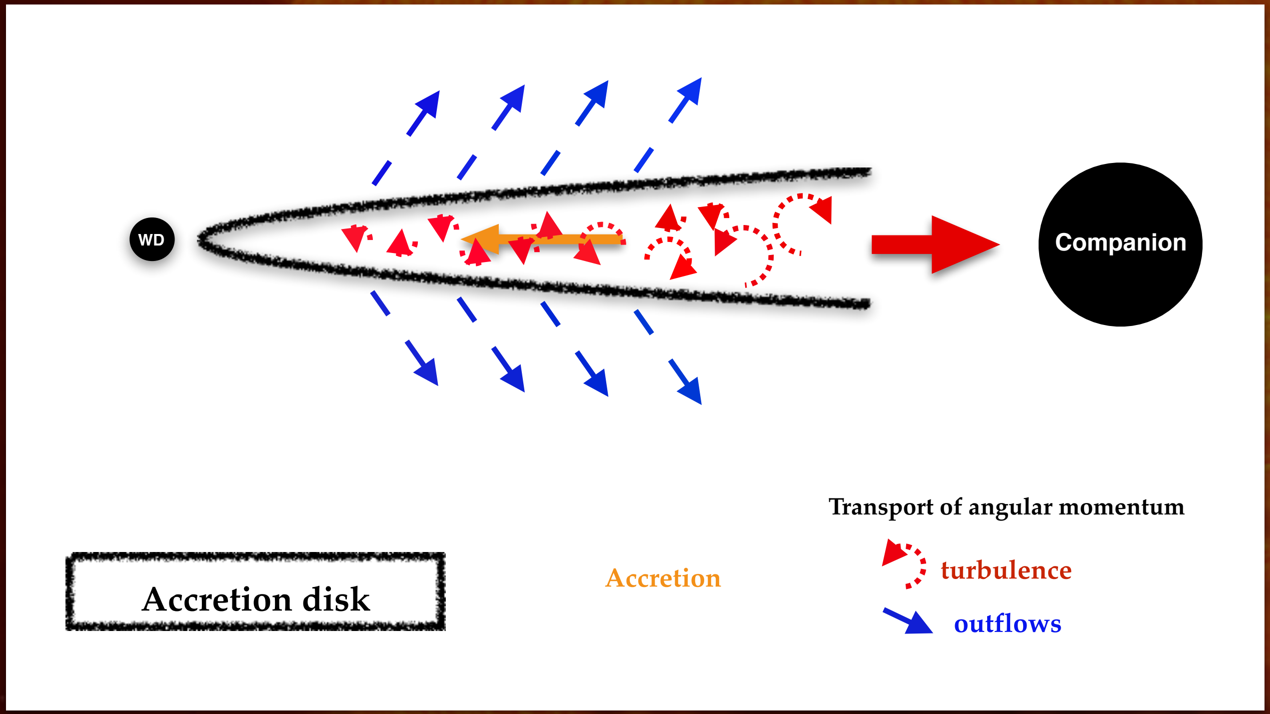


Scepi et al. 2018b submitted

Hot branch dominated by viscous accretion

Cold branch dominated by the wind-driven accretion

A new framework for the DIM



Disk with a wind will not behave as an α-disk.

Need to review observational constraints with a disk-wind model.

Turbulent case :

$$Q^+ = \frac{3GM\dot{M}}{4\pi R^3}\left[1 - \left(\frac{R_{in}}{R}^{1/2}\right)\right]$$

Turbulent + wind-driven case :

$$Q^+ = \frac{3GM}{8\pi R^{7/2}}\int_{R_{in}}^{R} \dot{M}_{R\phi} r^{-1/2} dr$$

X-ray flux in quiescence indicates higher accretion rates than predicted by the DIM model *(Mukai 2017)*

Conclusion

- ZNF simulations do not provide the α's to reproduce the light curves
- Net flux simulations show that wind-driven transport is a major dynamical component of DNe. Thus, we need to change the way we think about DNe.
- We can link observations to theory to provide new constraints on the wind-driven and turbulent transport.

Thank you for your attention

Model

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}) = 0$$

$$\rho \frac{\partial \boldsymbol{v}}{\partial t} + (\rho \boldsymbol{v} \cdot \boldsymbol{\nabla}) \boldsymbol{v} = -\boldsymbol{\nabla} \left(P + \frac{B^2}{8\pi} \right) + \left(\frac{\mathbf{B}}{4\pi} \cdot \boldsymbol{\nabla} \right) \mathbf{B} + \rho \big(-2\Omega \hat{\boldsymbol{z}} \times \boldsymbol{v} + 3\Omega^2 x \hat{\boldsymbol{x}} - \Omega^2 z \hat{\boldsymbol{z}} \big)$$

$$\frac{\partial E}{\partial t} + \boldsymbol{\nabla} \cdot [(E + P_t)\boldsymbol{v} - (\boldsymbol{v} \cdot \mathbf{B})\mathbf{B}] = -\rho \boldsymbol{v} \cdot \boldsymbol{\nabla} \Phi - \kappa_P \rho c (a_R T^4 - E_R)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \boldsymbol{\nabla} \times \left(\boldsymbol{v} \times \mathbf{B} - \frac{4\pi}{c} \eta \mathbf{J} \right)$$

Vertical stratification

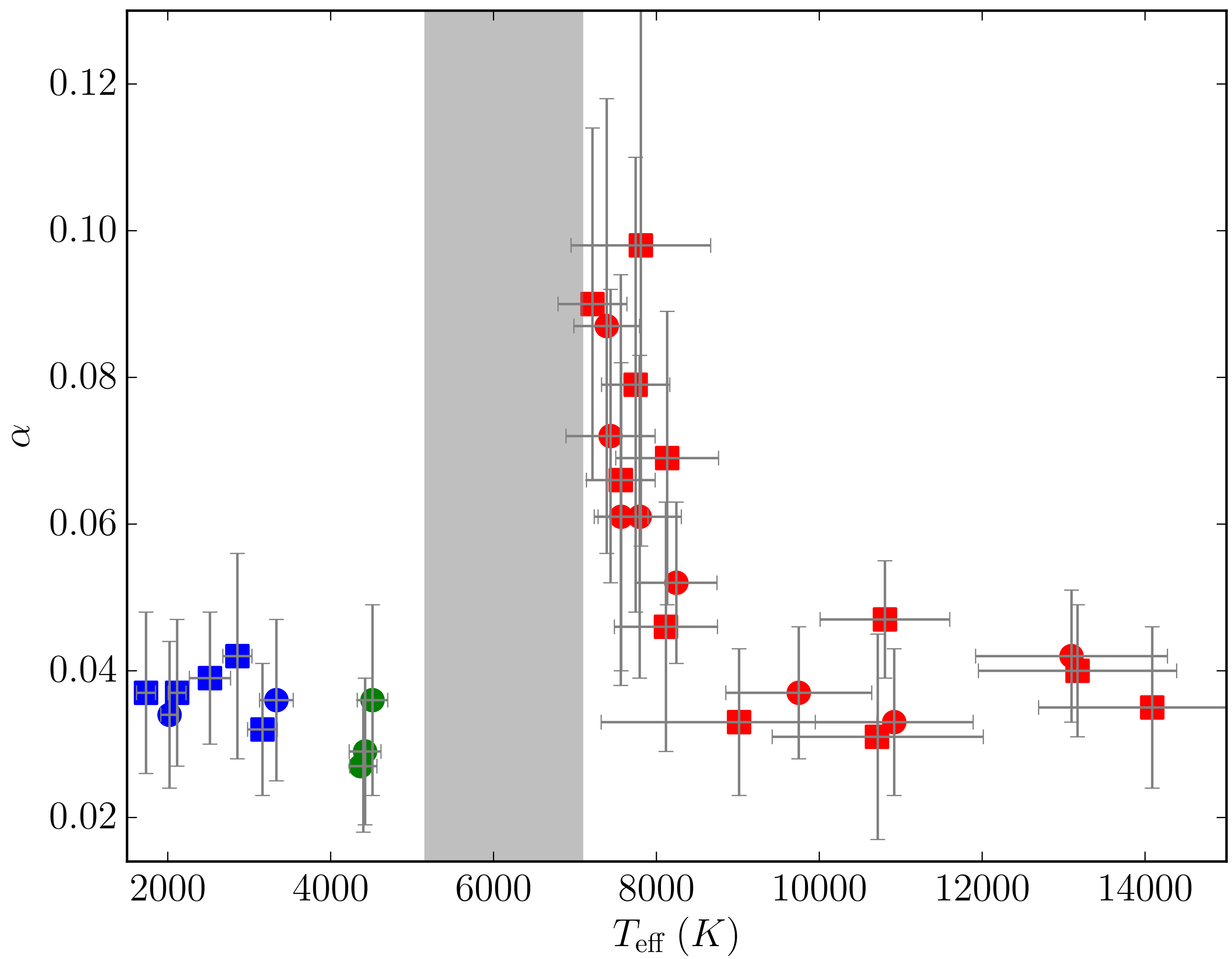
$$\frac{\partial E_R}{\partial t} - \boldsymbol{\nabla} \frac{c \lambda(R)}{\kappa_R \rho} \boldsymbol{\nabla} E_R = \kappa_P \rho c (a_R T^4 - E_R)$$

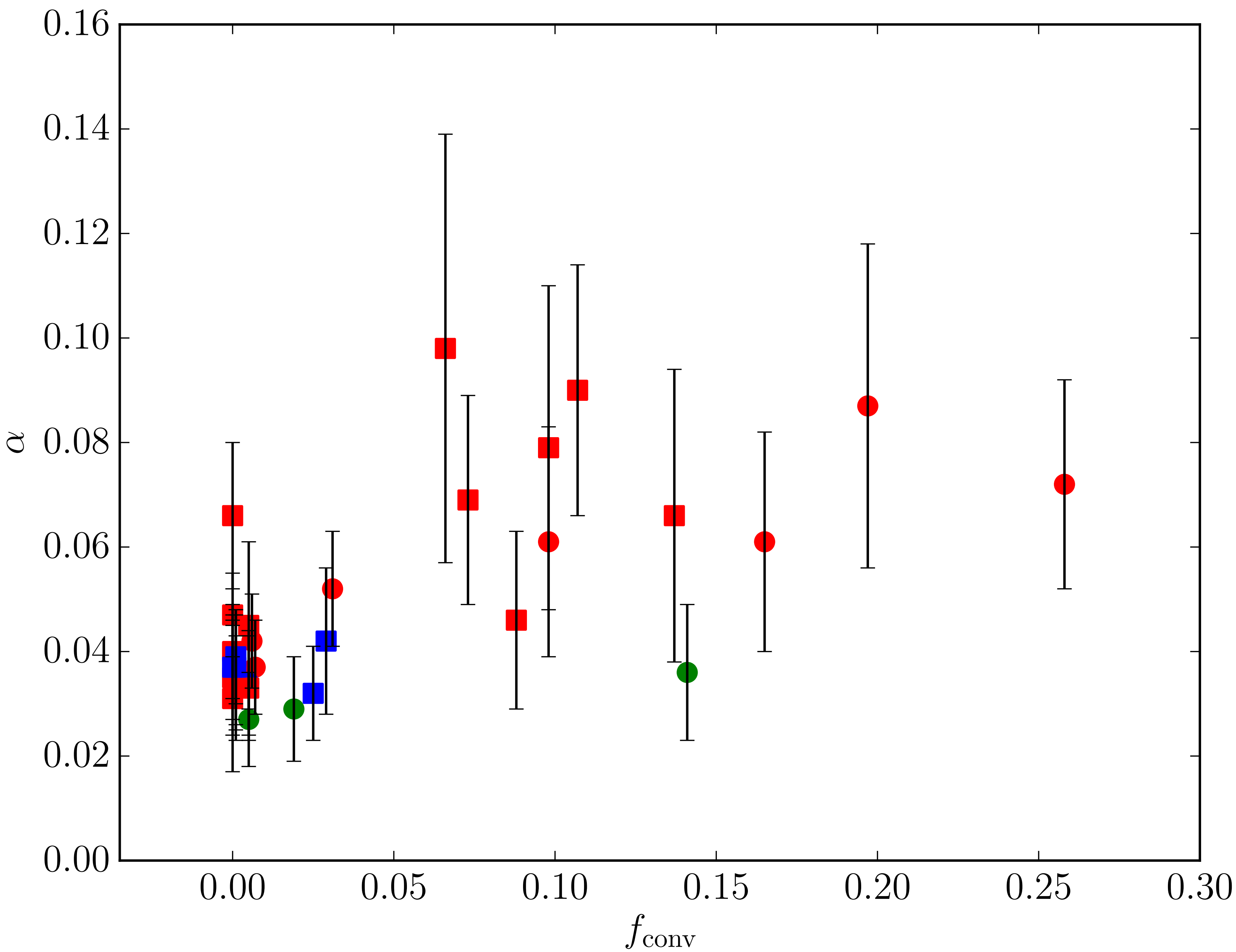
$$\frac{\partial \epsilon}{\partial t} = -\kappa_P \rho c (a_R T^4 - E_R)$$

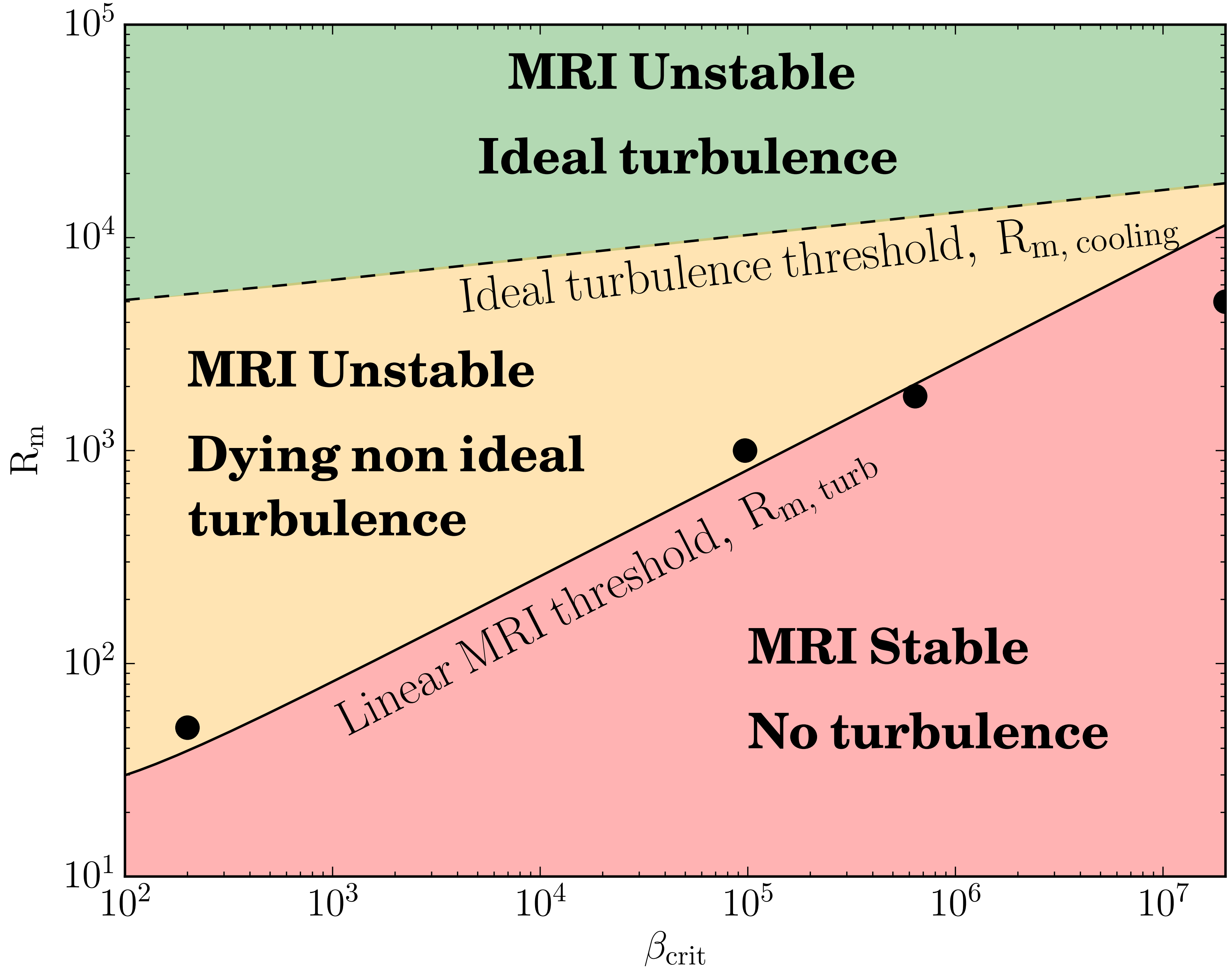
Radiative transfer and MHD are resolved separately *(Flock et al. 2013).*

Opacities, internal energy, thermodynamic quantities and resistivity are computed from tables

Scepi et al. 2018a

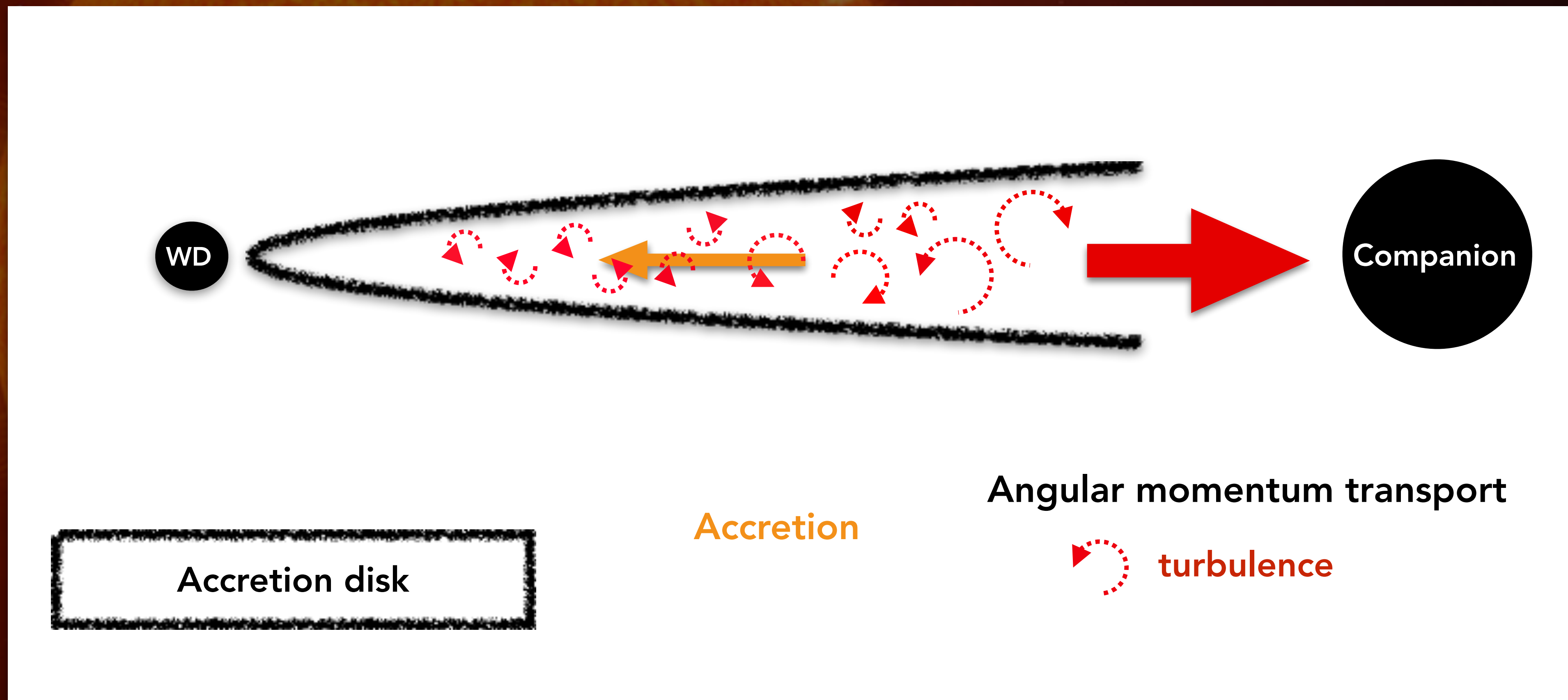



0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
α
0.00
0.05
0.10
0.15
0.20
0.25
0.30
f_{conv}



MRI Unstable
Ideal turbulence
Ideal turbulence threshold, $R_{m,\,cooling}$
MRI Unstable
Dying non ideal turbulence
Linear MRI threshold, $R_{m,\,turb}$
MRI Stable
No turbulence
R_m
β_{crit}
10^1
10^2
10^3
10^4
10^5
10^2
10^3
10^4
10^5
10^6
10^7

Historical framework : Turbulent/viscous accretion



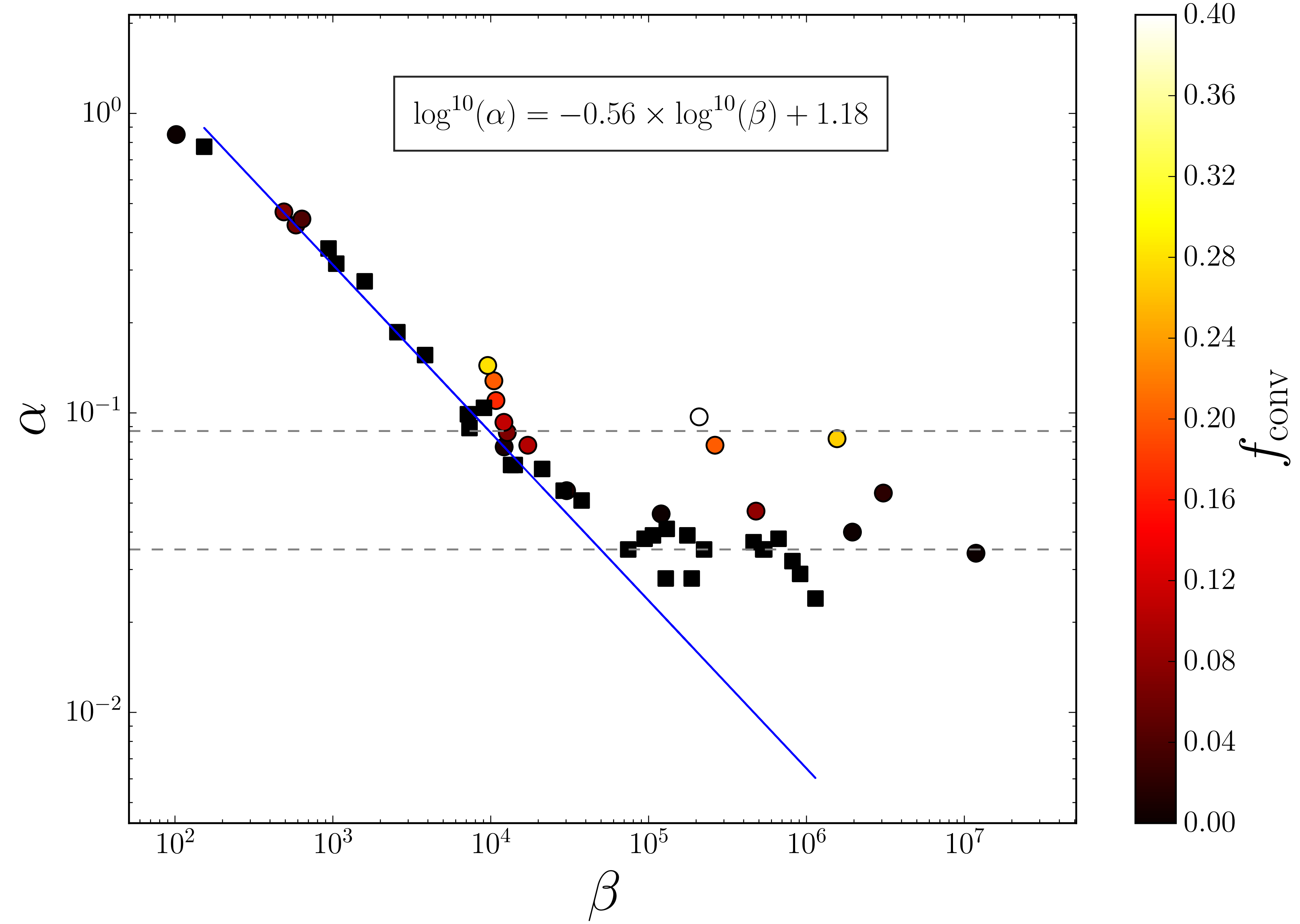
Turbulent transport modeled as a viscous transport

(Shakura & Sunyaev 1973)

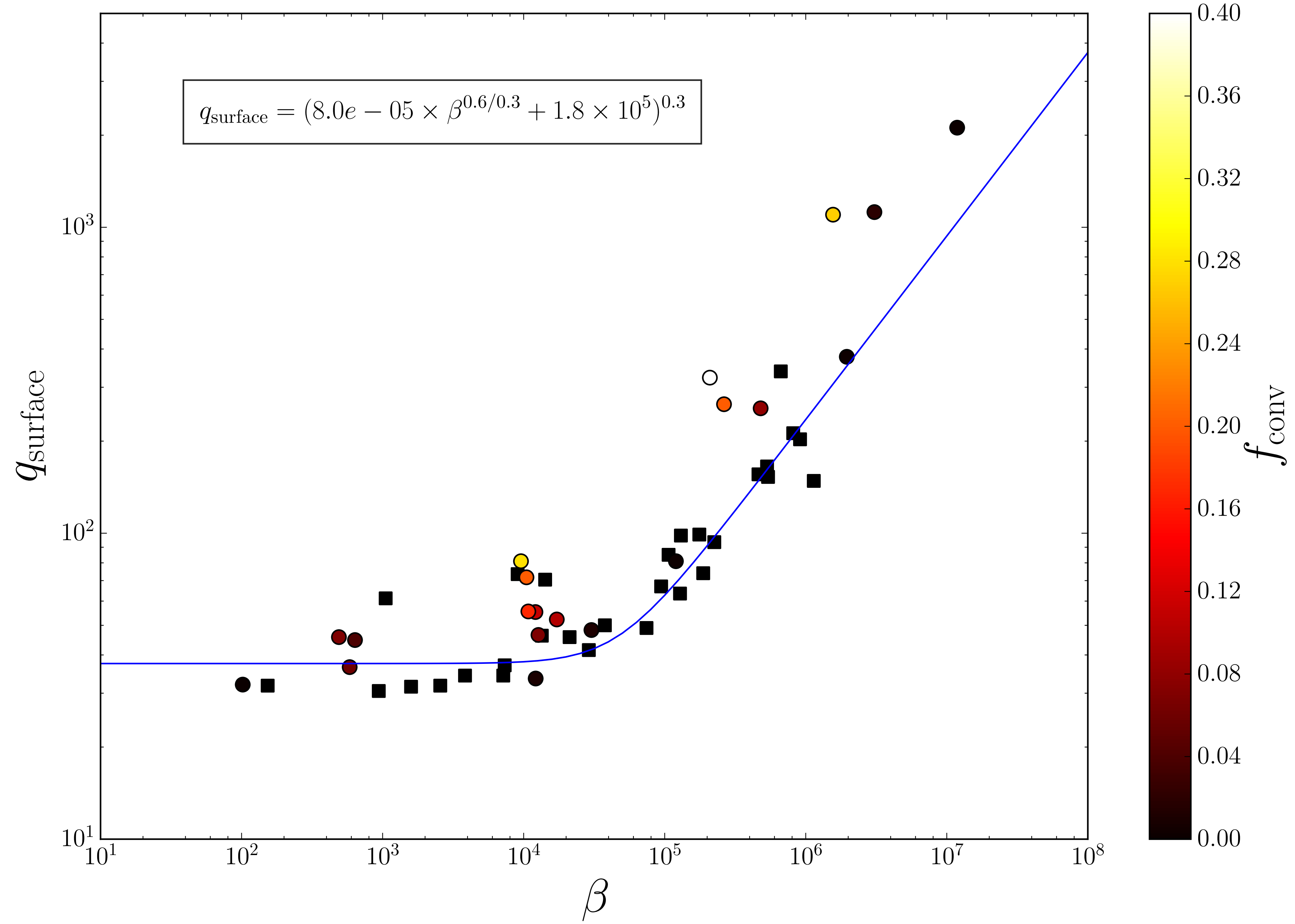
$$\nu_{\text{eff}} = \alpha c_s H$$

where turbulence is supposedly due to MRI.

(Balbus & Hawley 1991)



$\log^{10}(\alpha) = -0.56 \times \log^{10}(\beta) + 1.18$
10^0
10^{-1}
10^{-2}
α
10^2
10^3
10^4
10^5
10^6
10^7
β
0.40
0.36
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00
$f_{\rm conv}$



$q_{\rm surface} = (8.0e-05 \times \beta^{0.6/0.3} + 1.8 \times 10^5)^{0.3}$
$q_{\rm surface}$
β
$f_{\rm conv}$
0.40
0.36
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8