Structure formation in PPDs

surprises from wind dynamics

Geoffroy Lesur

with thanks to

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Étienne Martel (IPAG)
Jonathan Ferreira (IPAG)
François Ménard (IPAG)

MIAPP, Oct. 13 2021

MHDiscs
Revealing the dynamics of planet-forming discs

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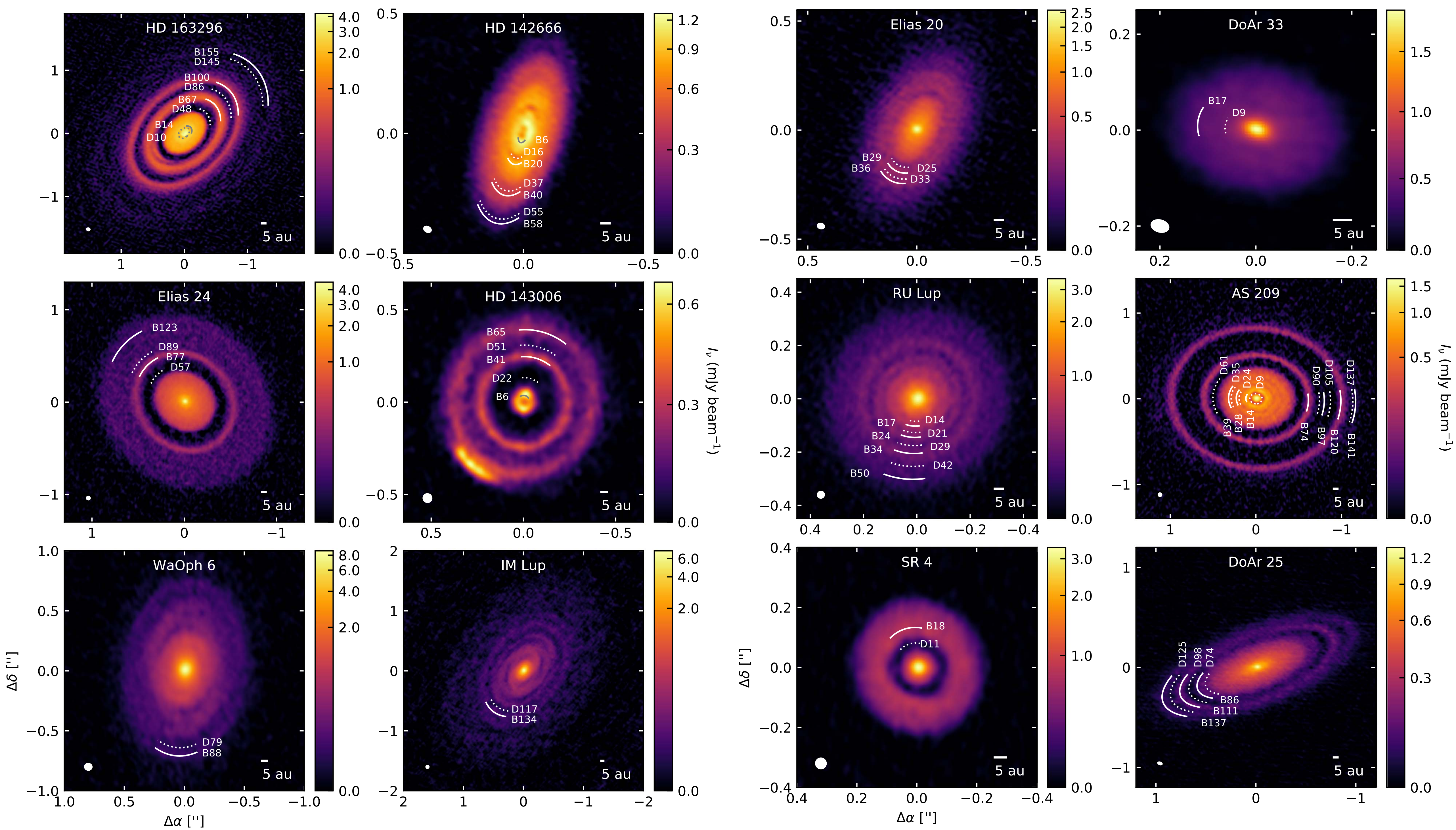
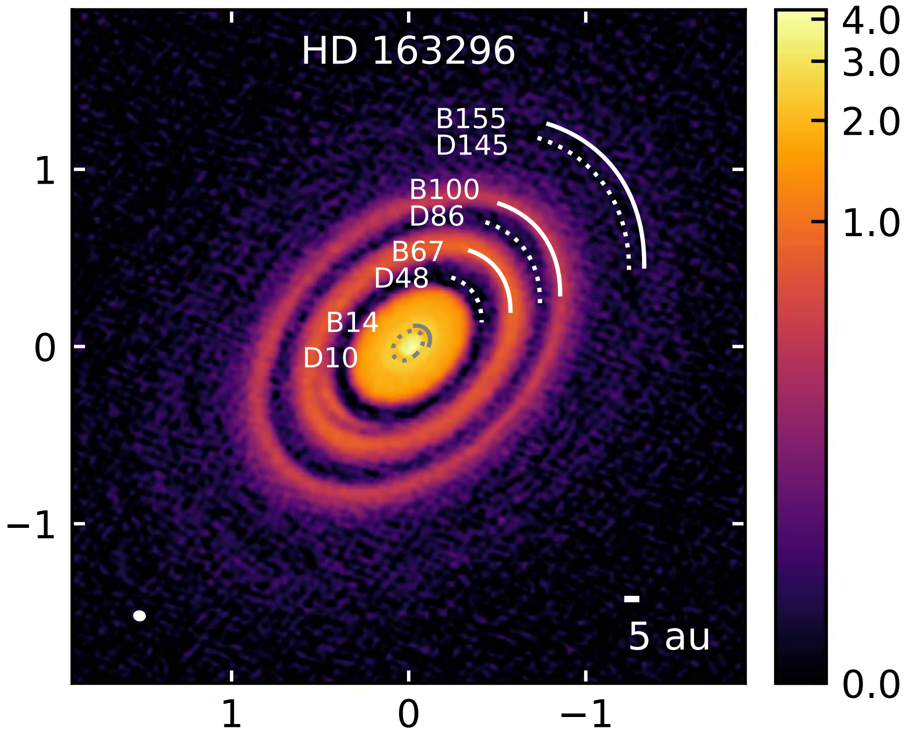
Institut de Planétologie et d'Astrophysique de Grenoble

Structures are common



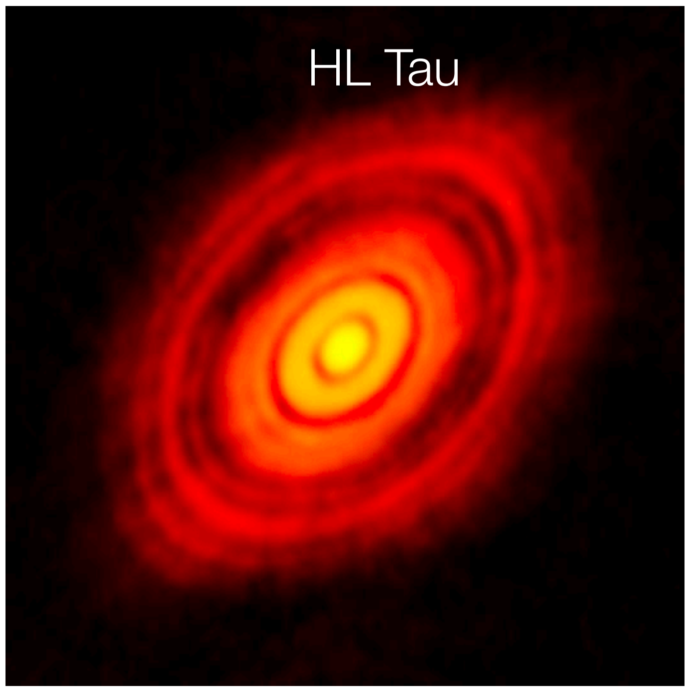
[Huang+ 2018]

Discs are accreting



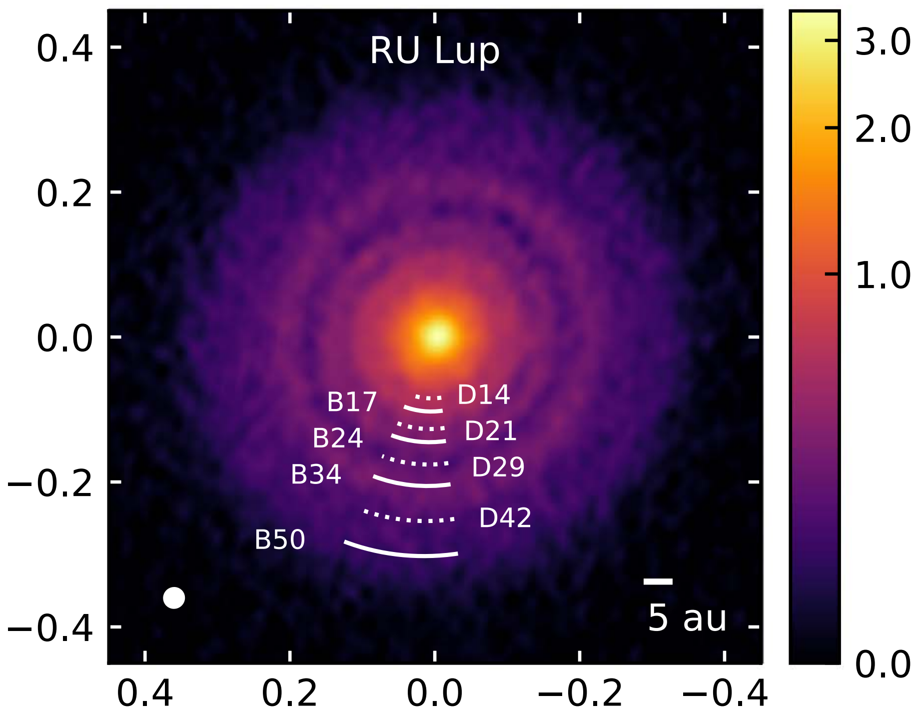
$\dot{M} = 4.5 \times 10^{-7} M_\odot/\mathrm{yr}$

[Mendigutia+2013]



$\dot{M} = 1 \times 10^{-7} M_\odot/\mathrm{yr}$

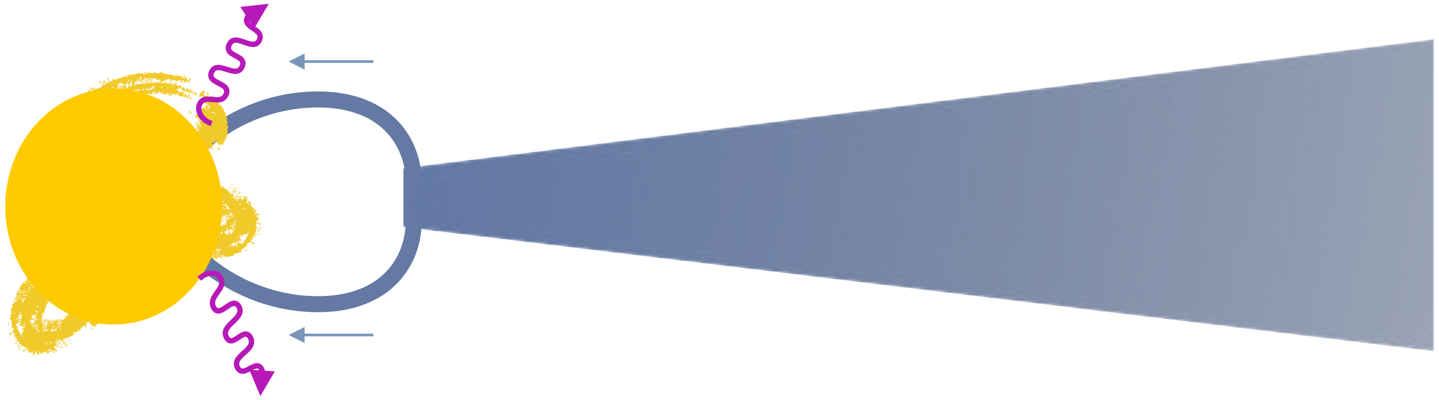
[Beck+ 2010]



$\dot{M} = 5 \times 10^{-8} M_\odot/\mathrm{yr}$

[Herczeg+ 2005]

… and $\dot{M}$ is measured at the stellar surface…



15 years ago, life was easy

The United Kingdom was a member of the European Union

George Bush was the US president

One didn't have to wear masks at all time

$$\alpha$$

Discs were fully described using Shakura & Sunyaev's alpha disc

Alas, things have changed…

- Protoplanetary discs are too weakly ionised for MHD to work as initially expected [Gammie (1996) and Perez&Chiang (2011)]

- α due to MHD turbulence is too small! incompatible with observed accretion rates [Bai & Stone (2013), Lesur et al. (2014)]

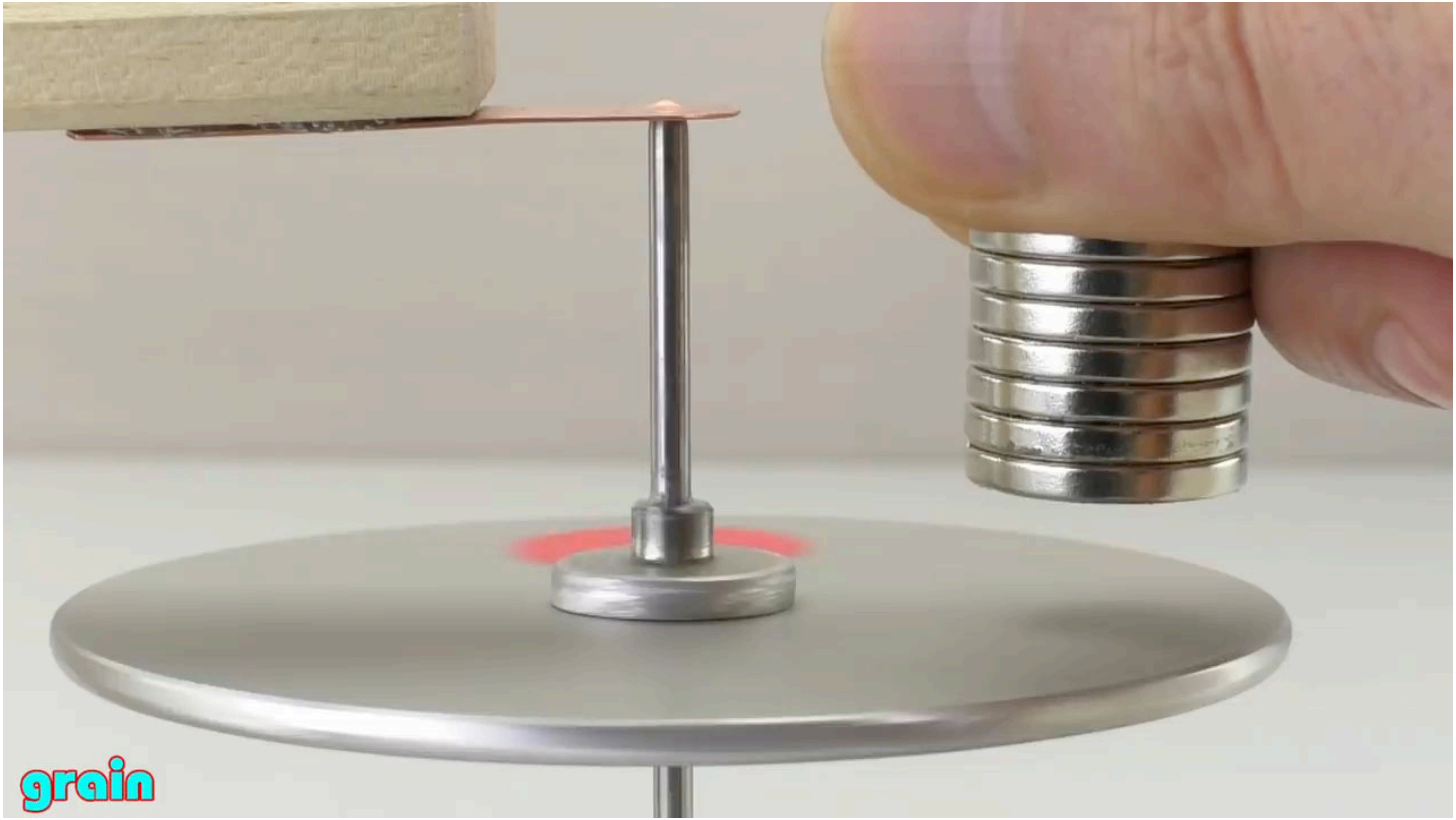
Mark Wardle

Arieh Konigl

« If a weakly ionised disc is plunged in ambiant magnetic field, one can still have accretion thanks to *magnetised outflows* »
[Wardle & Konigl 1993, Bai & Stone 2013]

→ new fashion: outflows/winds/jets…

A little experiment

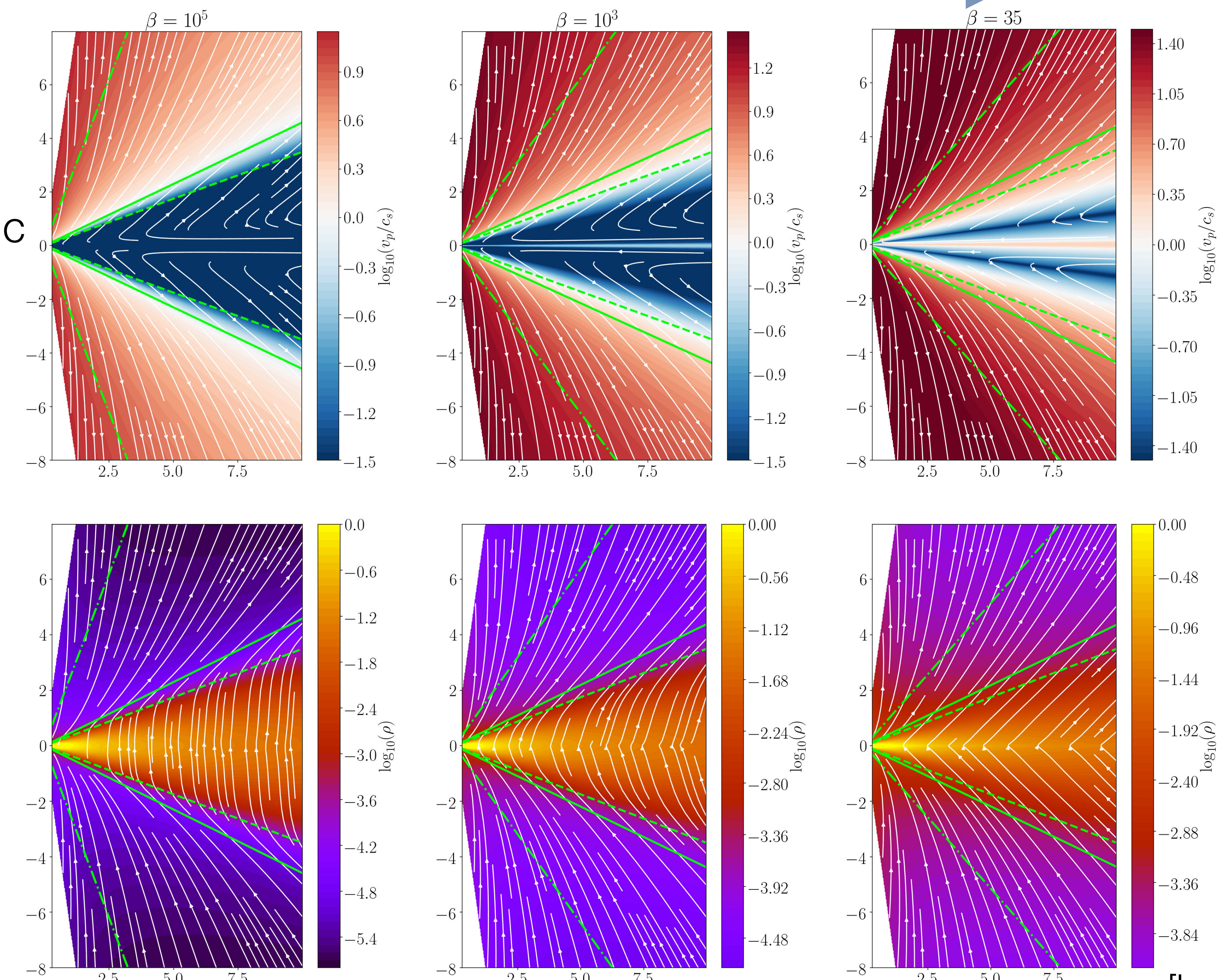


A sample of MHD disc winds

increasing field strength

Streamlines & sonic mach number

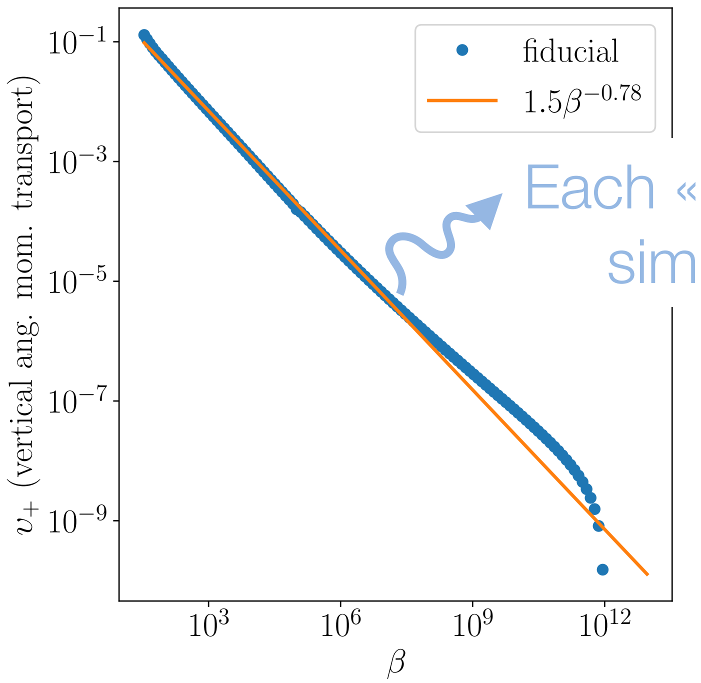
Fieldlines & gas density



[Lesur 2021]

Fig. 2. Flow topology in the fiducial run (ambipolar diffusion only $\Lambda_A = 1$). Top row: poloidal streamlines (white) and log of the sonic Mach number. Bottom row: poloidal field and log of density, normalised so that the midplane density at $R = 1$ is unity. Note that the colour scales are identical between the columns. From left to right the disc magnetisation increases: $\beta = 10^5$; 10^3 ; 35. The green lines denotes critical lines of the flow: Alfv'enic (plain) and fast magnetosonic (dot-dashed). The green dashed line represents the disc "surface" where the flow becomes ideal, arbitrarily located at $z = 3.5h$ for all of the solutions.

Relating to the field strength in a wind-driven disc



Each « dot » is a simulation

Scaling laws in self-similar simulations [Lesur 2021]

Accretion rate

surface density

$$\dot{M}_{\rm acc} = 1.6\times 10^{-8}\left(\frac{\Sigma}{10\,{\rm g.cm^{-2}}}\right)^{0.22}\left(\frac{R}{10\,{\rm A.U.}}\right)^{2.08}\left(\frac{M}{M_\odot}\right)^{-0.28}$$
$$\times\left(\frac{\varepsilon}{0.1}\right)^{-0.78}\left(\frac{B_z}{1\,{\rm mG}}\right)^{1.56} M_\odot/{\rm yr.}$$

Disc aspect ratio (H/R)

$$\dot{M}_{\rm wind} = 1.07\,\dot{M}_{\rm acc}\left(\frac{\Sigma}{10\,{\rm g.cm^{-2}}}\right)^{0.09}\left(\frac{B_z}{1\,{\rm mG}}\right)^{-0.18}$$

- Mass accretion is mostly controlled by the magnetic field intensity and depends *only weakly* on Σ
- Mass loss rate is approximately equal to mass accretion rate.

Pressure bumps and rings

How winds can spontaneously create pressure bumps

Antoine Riols
Former postdoc @ IPAG
now ONERA

How to make a steady pressure bump?

Case I: viscosity

Viscous theory:

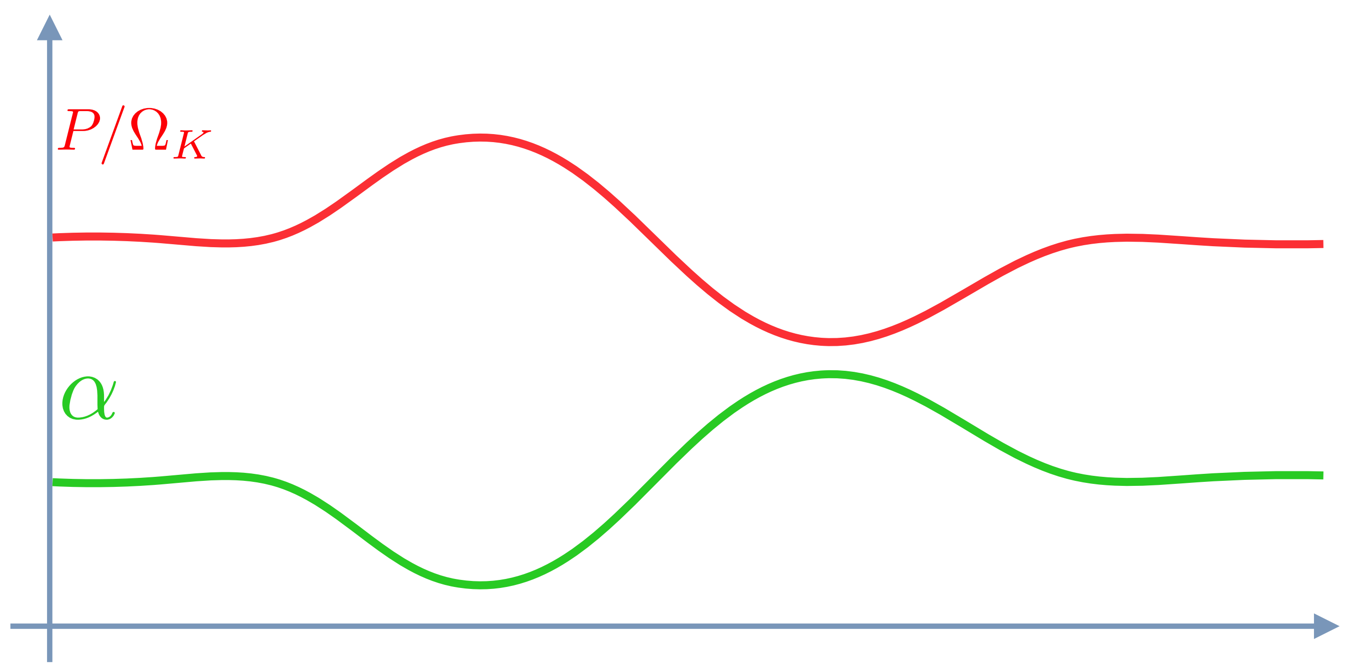
$$\frac{\partial \Sigma}{\partial t} + \frac{1}{2\pi R}\frac{\partial}{\partial R}\dot{M}_{acc} = 0,$$

steady state

$$\frac{\dot{M}_{acc}\Omega_K}{4\pi} = \frac{1}{R}\frac{\partial}{\partial R}\left(R^2 \alpha P\right)$$

$$\alpha P = \frac{\dot{M}_{acc}}{2\pi}\Omega_K$$

→ viscosity and pressure are anti-correlated



→ Pressure bumps are expected in association with low viscosity regions

How to make a steady pressure bump?

Case II: winds

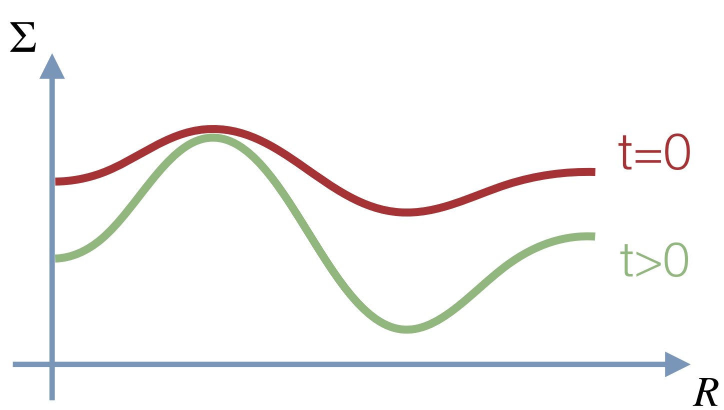
Viscous theory+wind:

wind mass-loss rate parameter

$$\frac{\partial \Sigma}{\partial t} + \frac{1}{2\pi R}\frac{\partial}{\partial R}\dot{M}_{acc} = -\zeta \Sigma \Omega_K ,$$

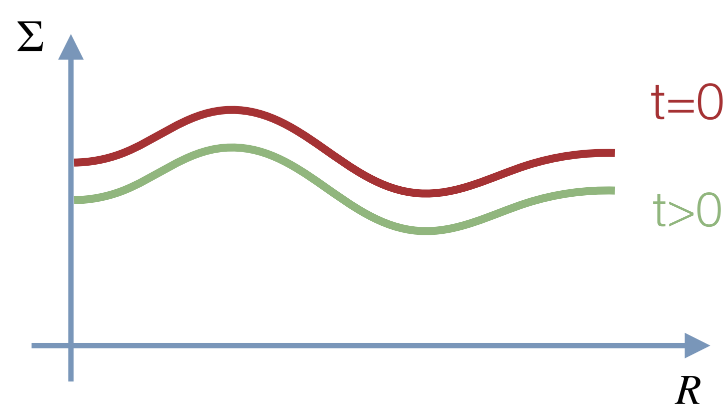
3 possible cases (ignoring $\dot{M}_{acc}$ for the moment)

$\frac{d\zeta}{d\Sigma} < 0$



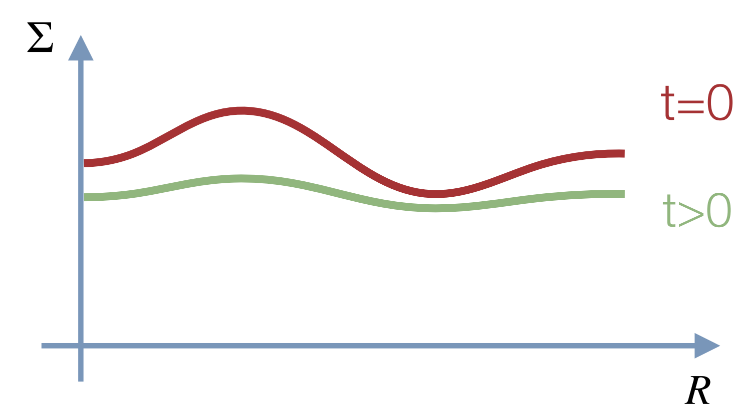
ex: MHD-driven winds
(assuming constant B)

$\frac{d\zeta}{d\Sigma} = 0$



ex: photo-evaporative winds

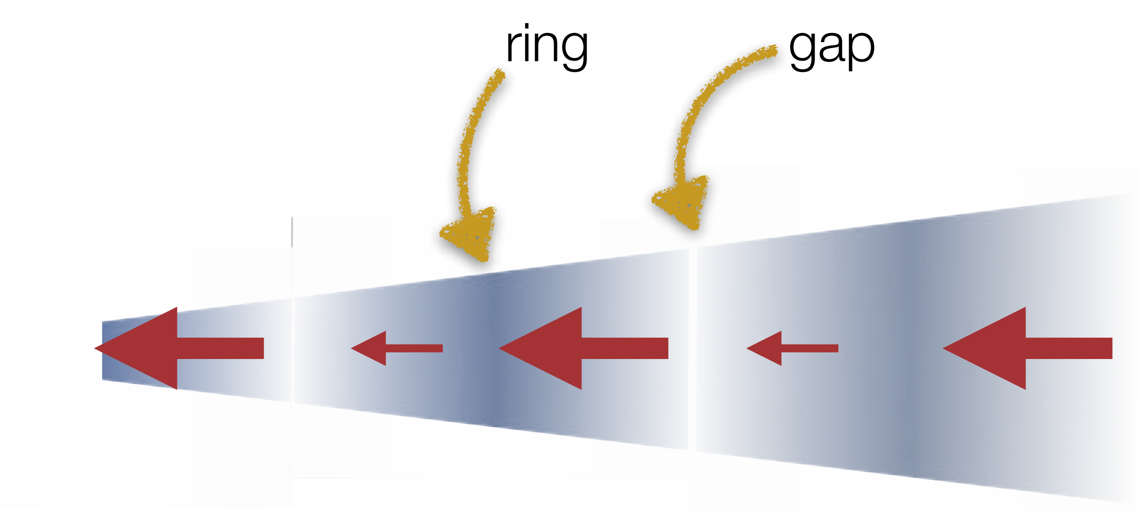
$\frac{d\zeta}{d\Sigma} > 0$



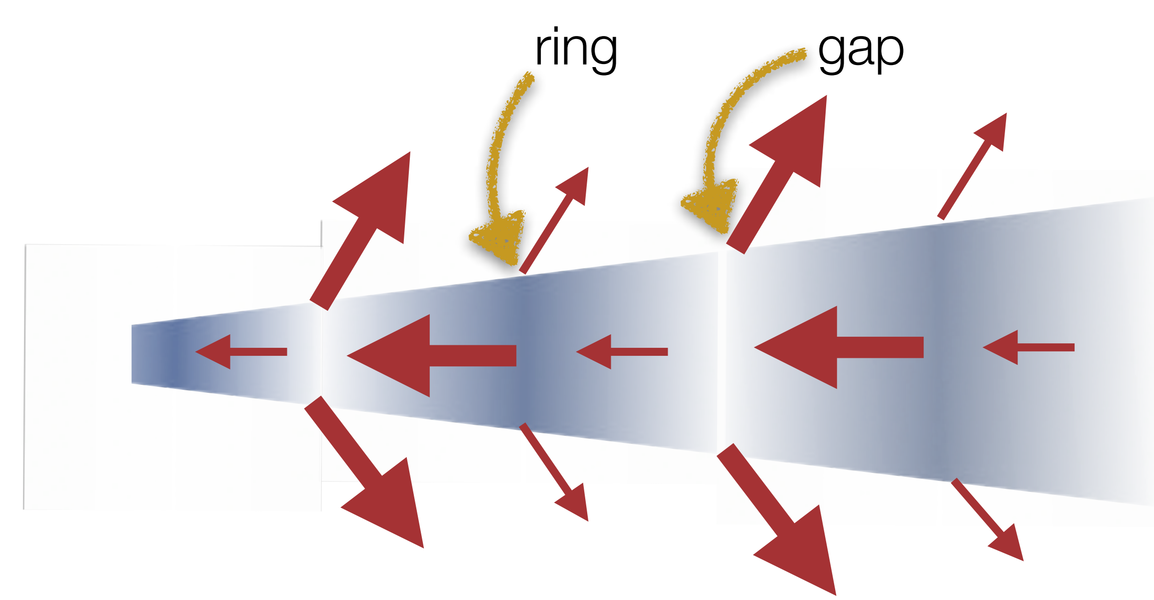
Pressure bumps are expected in association with low mass-loss rate regions

Viscosity or wind-driven?

- Viscosity maxima in gaps (more turbulence?)
- Accretion flow diverges from gaps

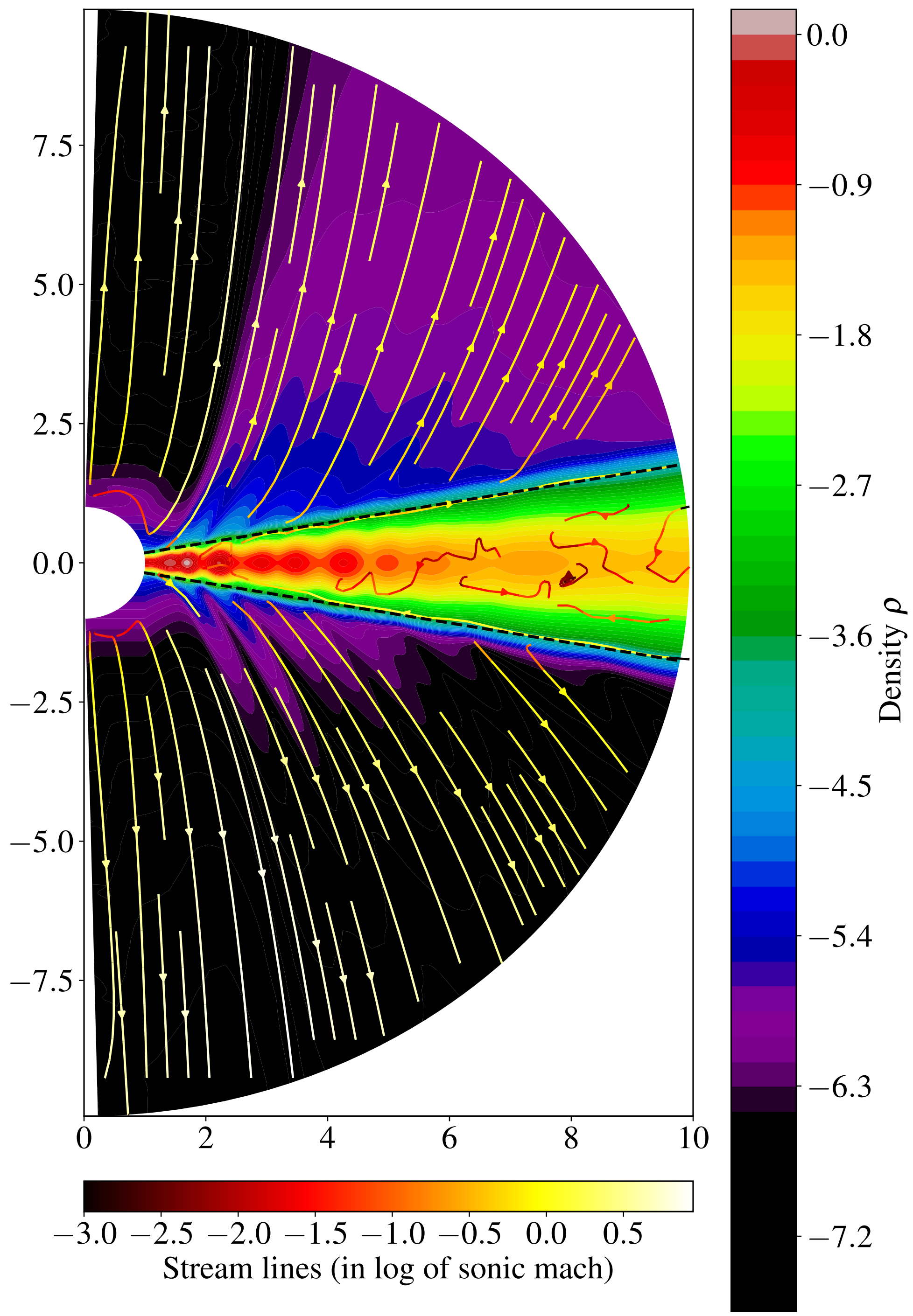


- Faster wind velocity in gaps
- Accretion flow converges towards the gaps (it tries to « fill » the gaps)



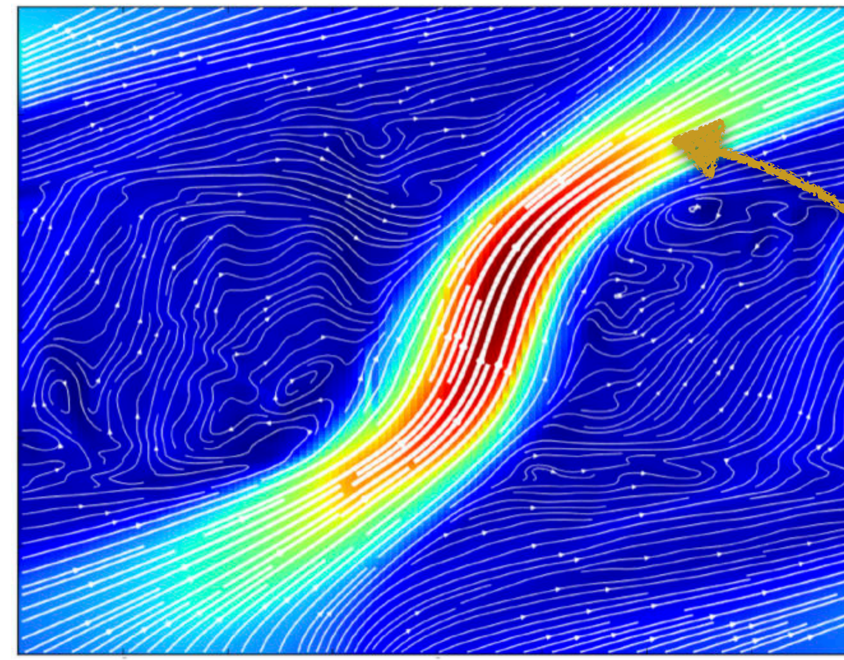
Example: ring formation

In wind-emitting discs

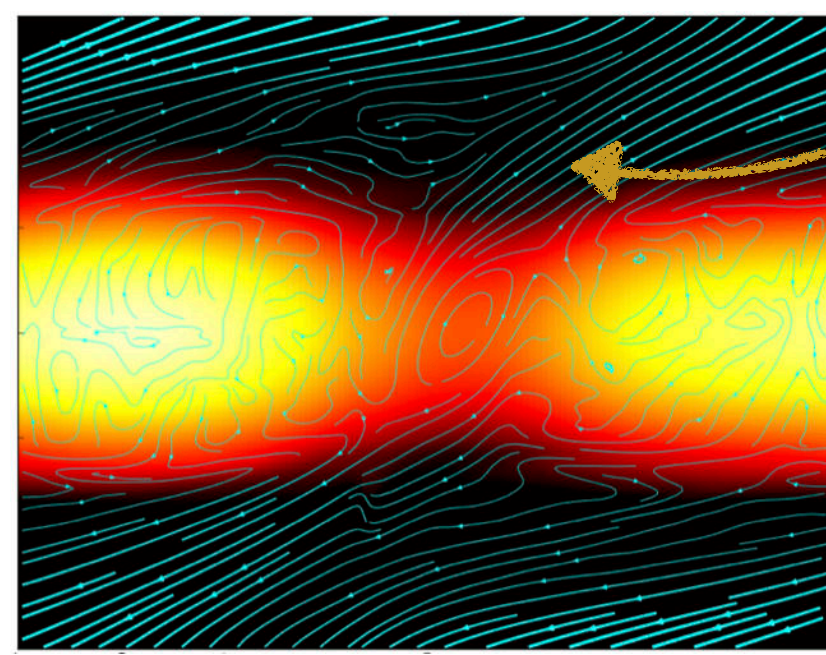


[Riols+2020]

Magnetic field lines



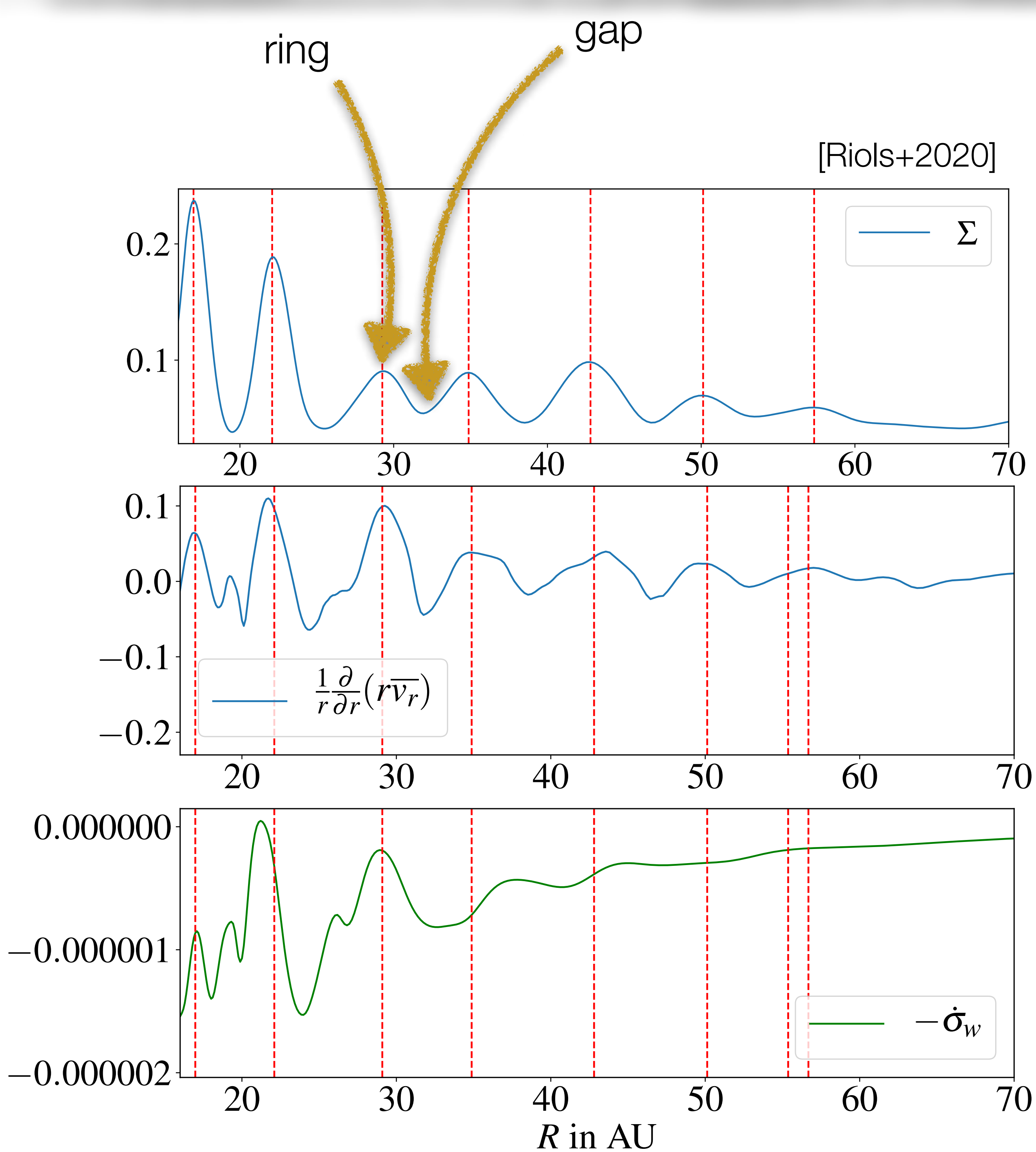
Streamlines



MHD wind « plume »

[Riols & Lesur 2019]

Viscous or wind-driven?



Rings and gaps regularly spaced

Density contrast $\lesssim 2$

Radially *convergent* flow in rings

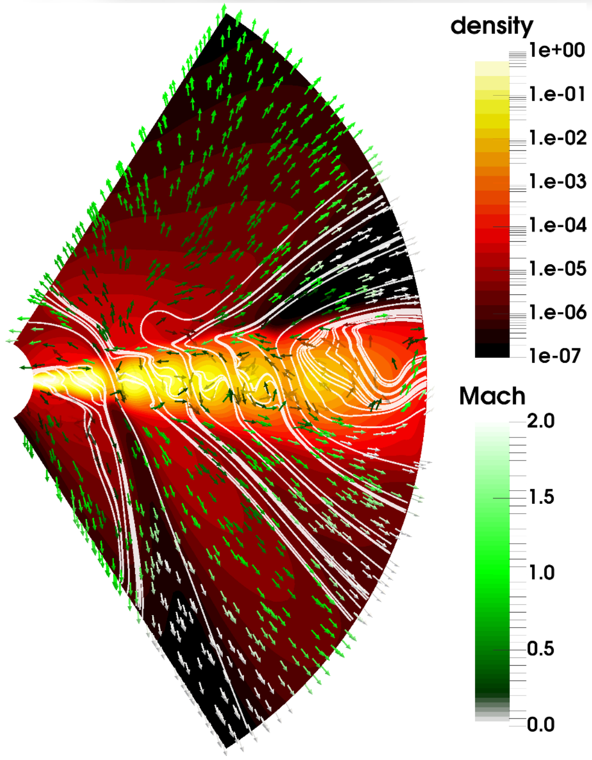
(tries to fill the gap)

Larger mass loss rate in gaps

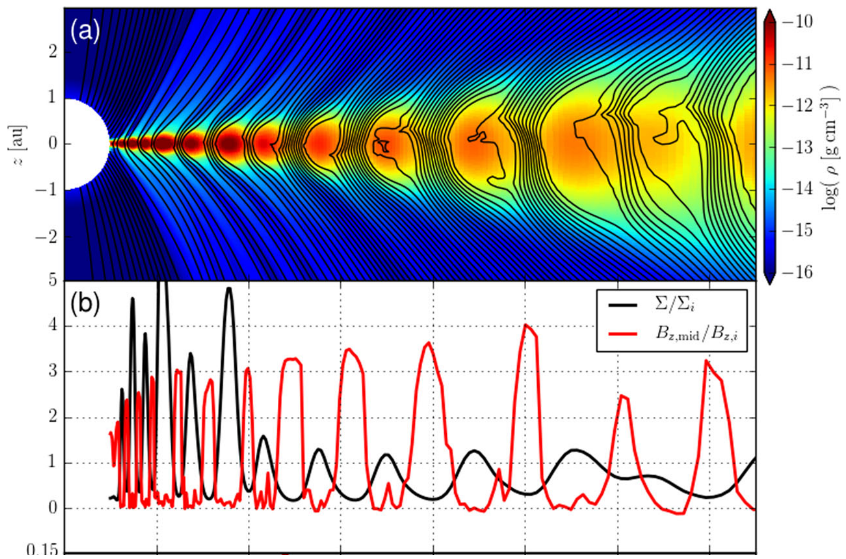
(absolute value)

→ Wind-driven structure formation

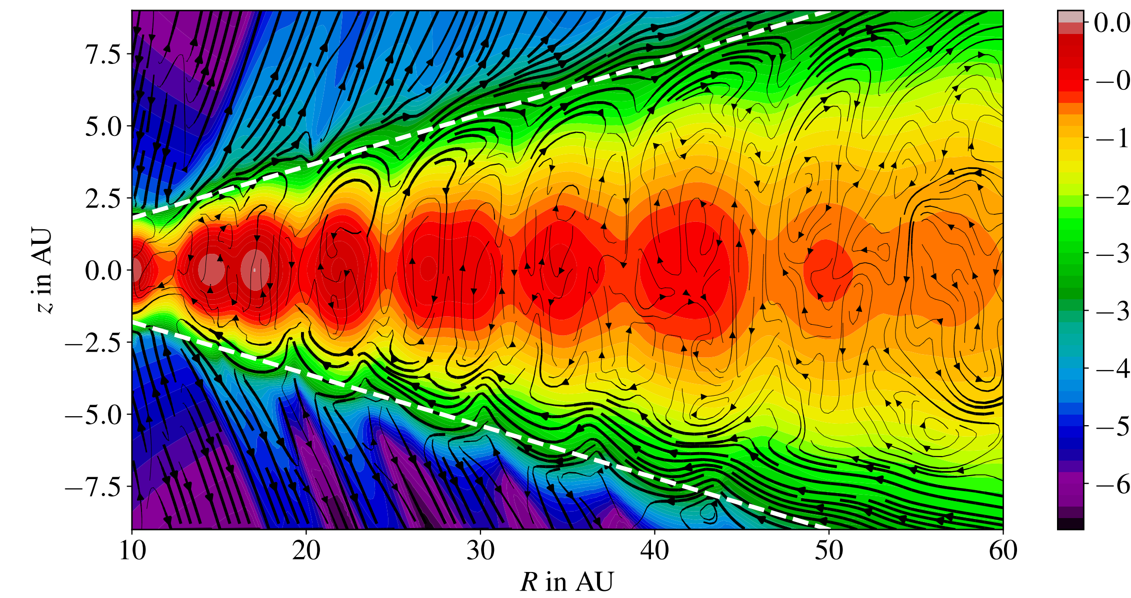
Is this general?



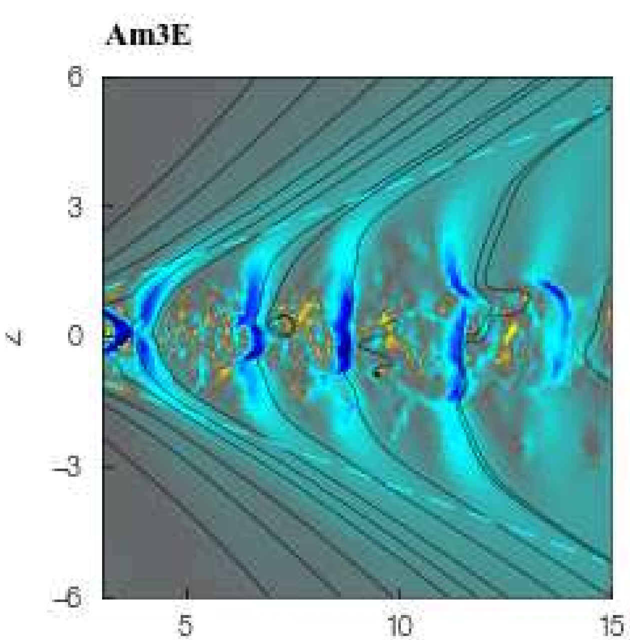
[Béthune+2017]



[Suriano+2018]



[Riols+2020]



[Cui & Bai 2021]

Common ingredients are

- Ambipolar diffusion (valid for R>~5AU)
- Large scale magnetic field (fossil field?) B≥a few mG @ 10 AU ($\beta \lesssim 10^4$)

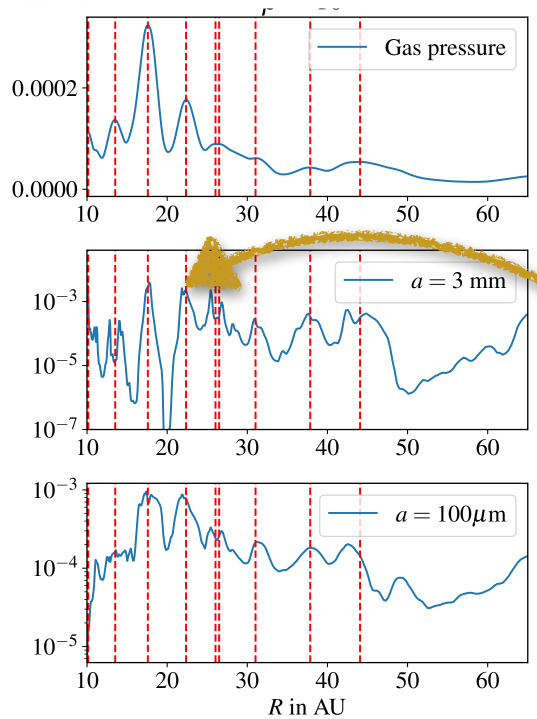
Dust traps and observables

[Riols+2020]

gas

3mm dust

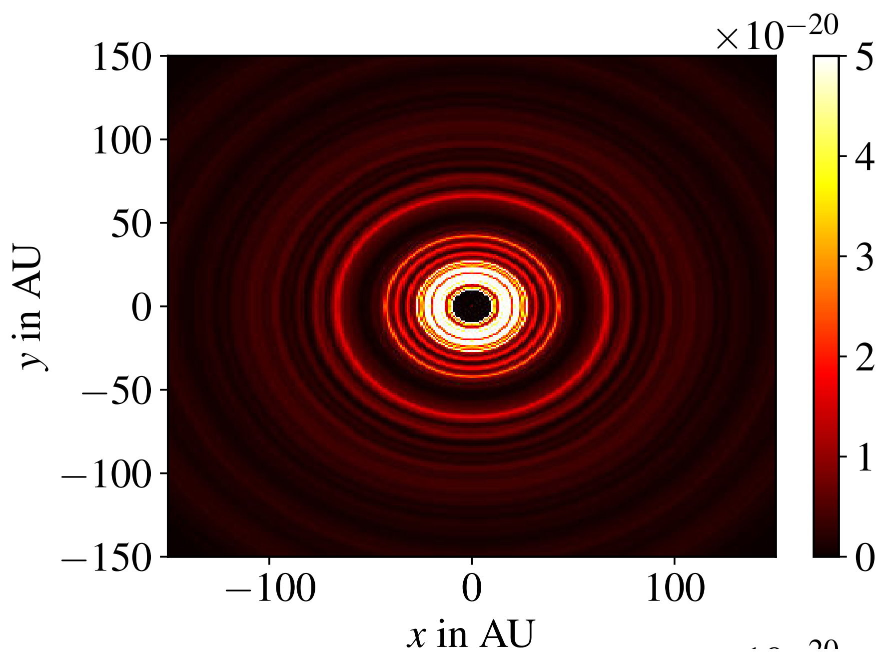
100μm dust



« dusty » ring

The « gas rings » produced by winds are steady-state pressure bumps (as expected)

They act as dust traps



Synthetic ALMA image @1mm

Flux density and spectral index

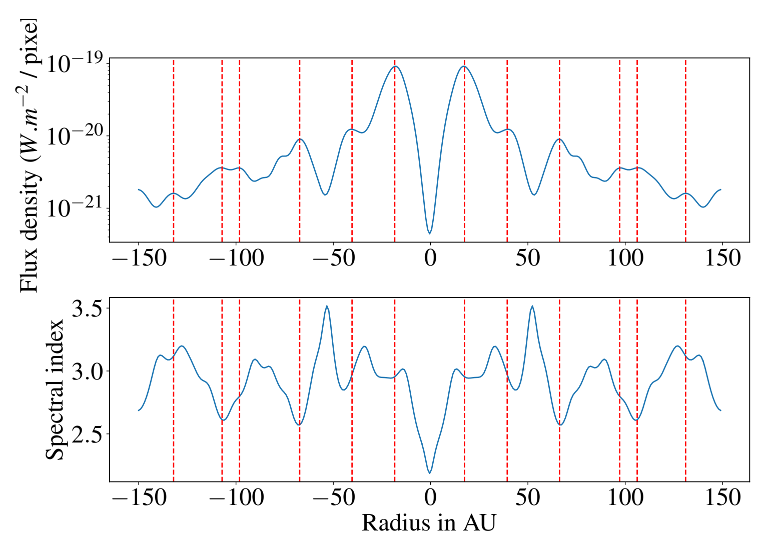


Fig. 14. *Top panel*: convolved flux density νF_ν in W m^{-2} pixel^{-1} as a function of radius. *Bottom panel*: spectral index $\alpha_s = d \log F(\nu)/d \log \nu$ as a function of radius measured between λ = 1 mm (ALMA band 7) and λ = 3 mm (ALMA band 3).

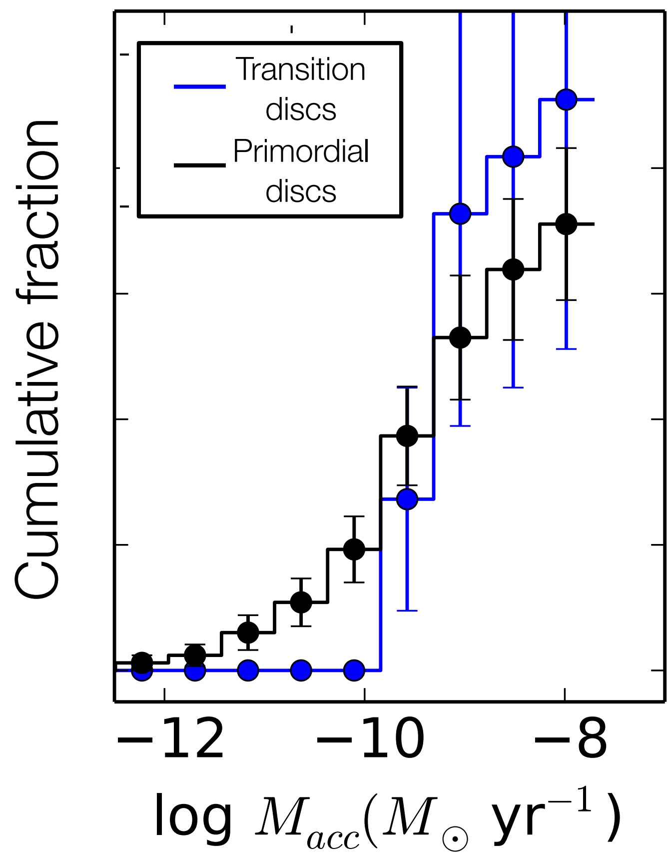
MHD wind spontenaously create visible dust ring structures

Transition discs

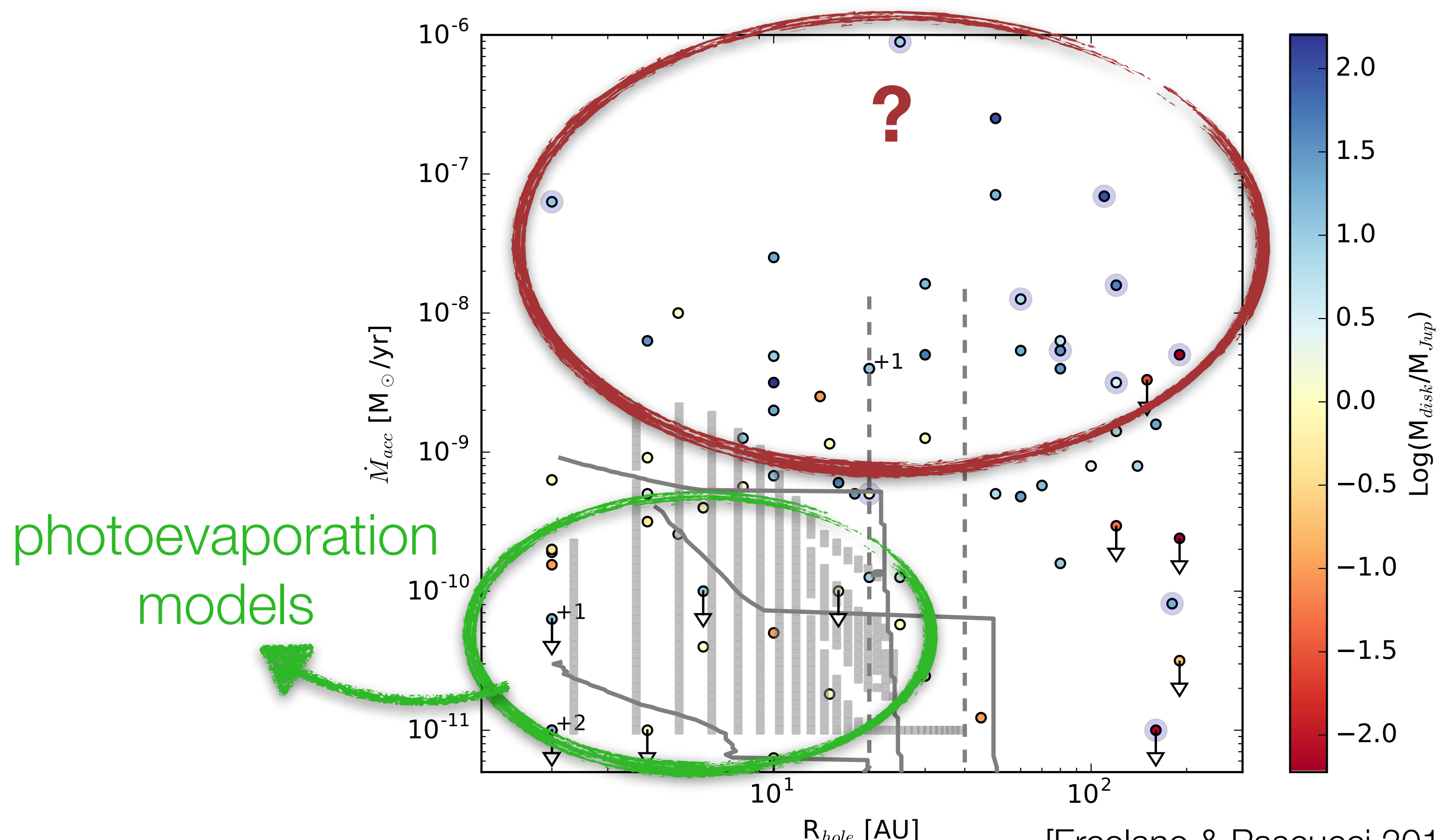
MHD disc winds as a planet-free model of transition discs

Etienne Martel
PhD student @ IPAG

Accretion in transition discs



[van der Marel+2018]



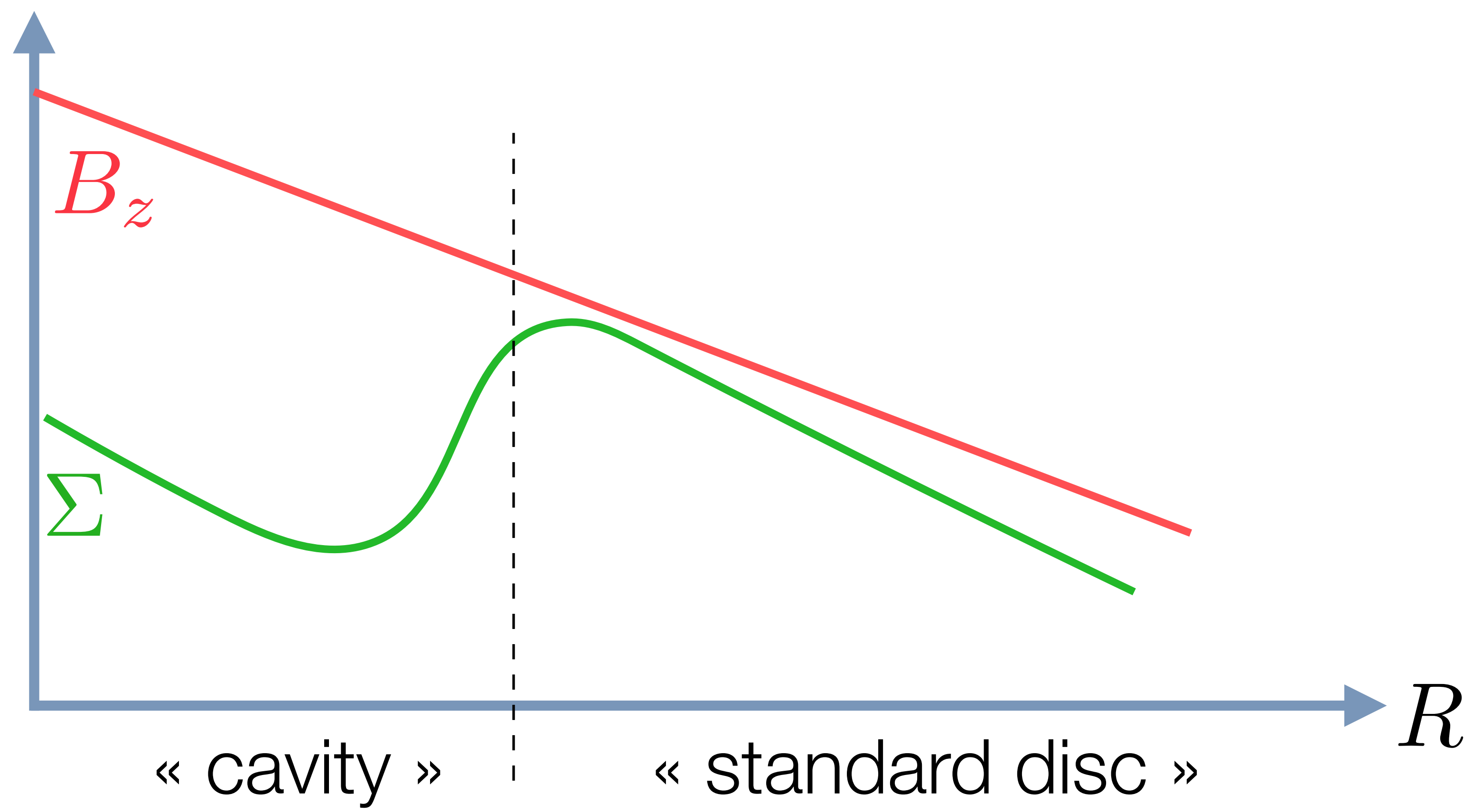
[Ercolano & Pascucci 2017]

- Transition discs exhibit accretion rates distribution similar to primordial discs
- Photoevaporation alone cannot explain high $\dot{M}_{\rm acc}$ transition discs
- In a viscous disc $\dot{M}_{\rm acc} \propto \alpha\Sigma$ → low $\dot{M}_{\rm acc}$ is expected in a cavity!

Accretion in TDs calls for a non-viscous accretion mechanism

The model

Largely inspired from Combet & Ferreira 2008

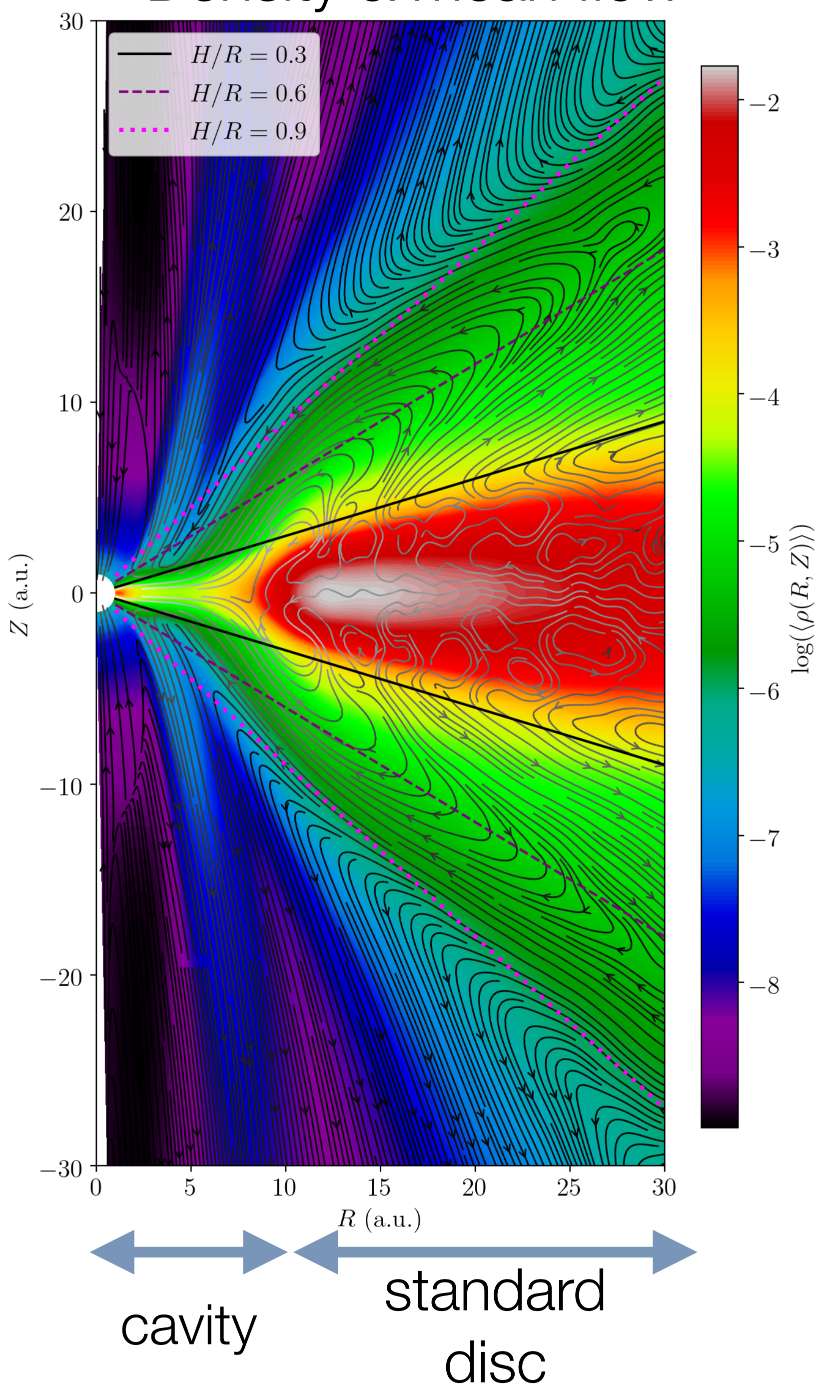


- Cavity only in surface density
- Bz follows a power law distribution
- Cavity and standard disc both weakly ionised → non-ideal MHD (mostly ambipolar diffusion, see Wang & Goodman 2017)

Some results

[Martel & Lesur in prep]

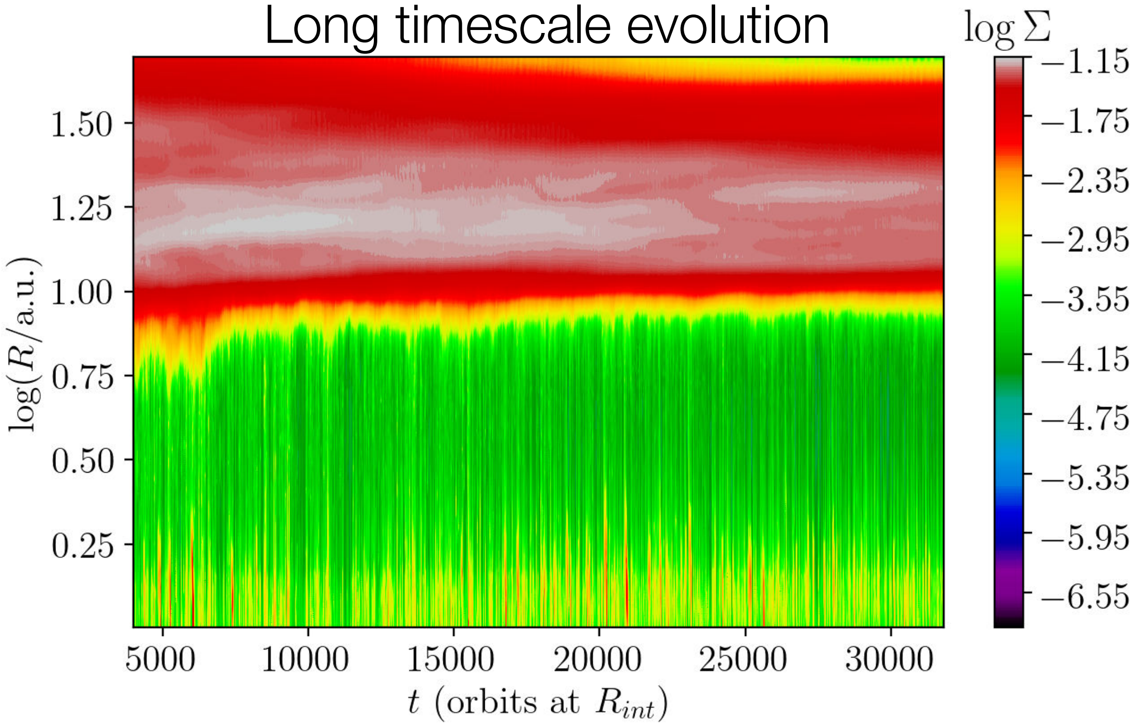
Density & mean flow



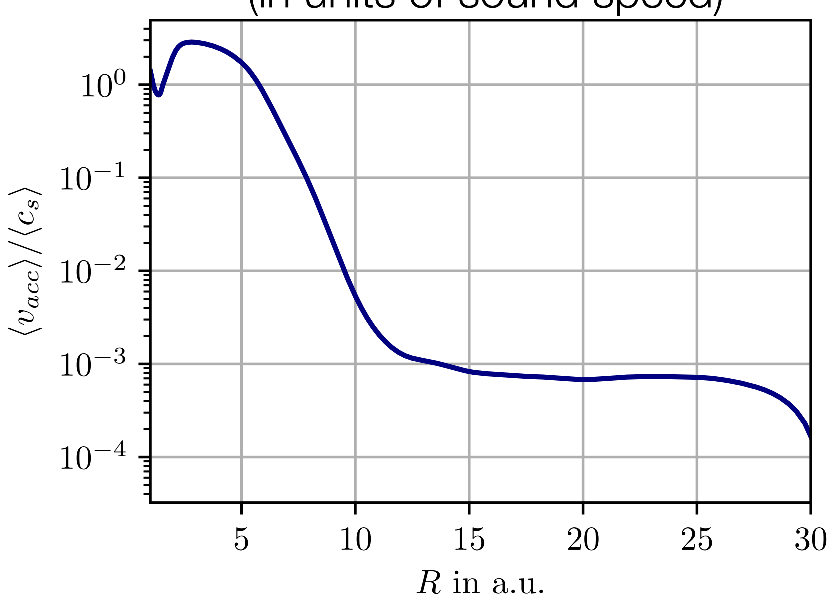
cavity

standard disc

Long timescale evolution



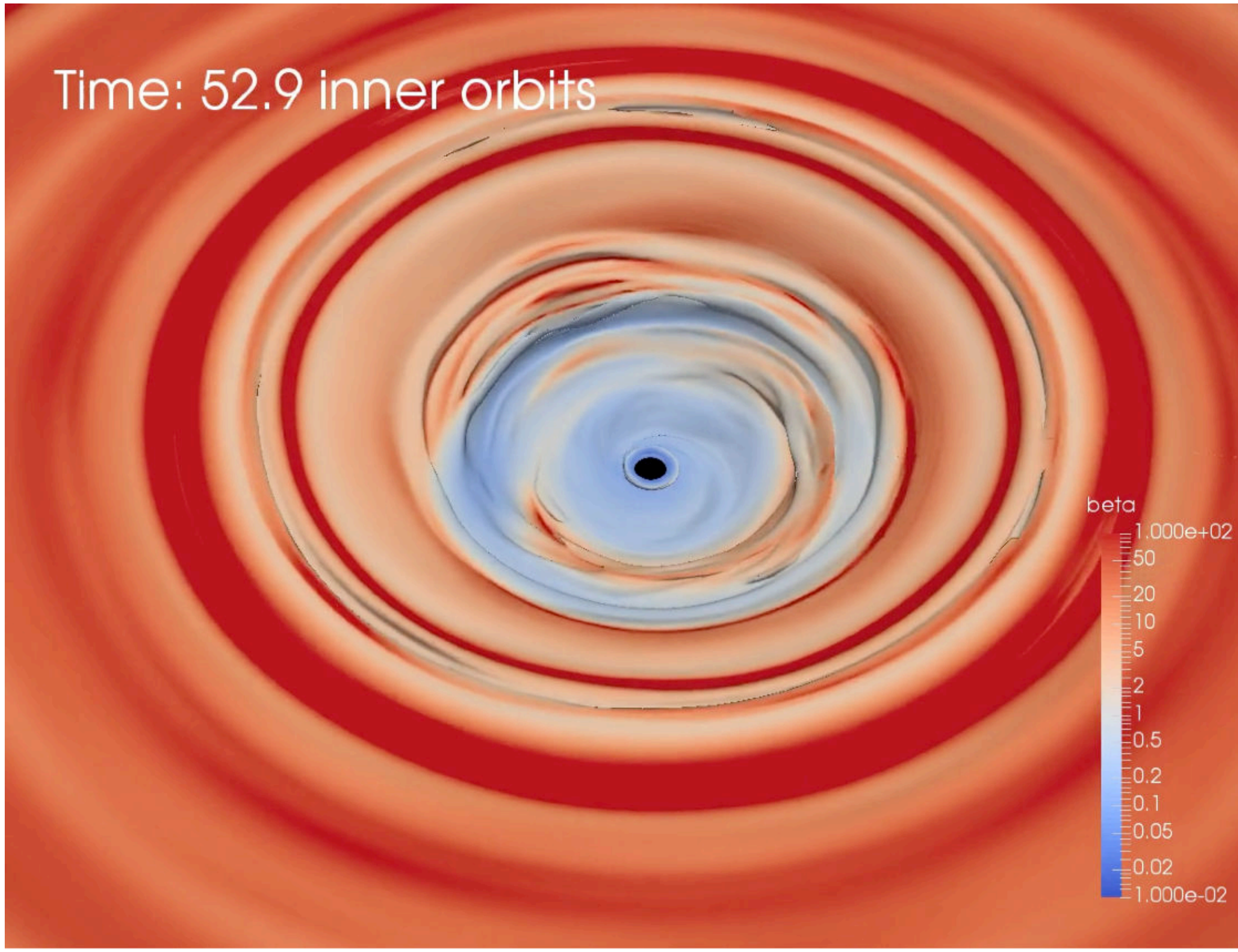
Accretion velocity
(in units of sound speed)



MHD winds successfully produce steady TD-like cavities
with accretion rates that match « standard » discs

Conclusions

- MHD disc winds transport mass according to the local magnetic field strength
- They can spontaneously carve gaps in the disc structure
- Could explain high accretion rates in transition discs (similar to MADs around black holes?)



Magnetised transition disc in action